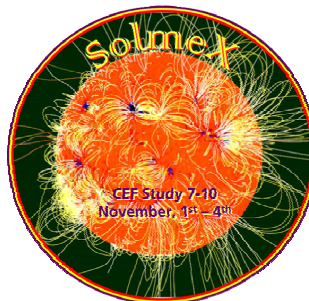


**Institute of Space Systems
System Analysis Space Segment**

**Feasibility Study
SolmeX**

Concurrent Engineering Study Report



**DLR-RY-CE-R005-2010-2
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in November 2010,
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Study Team and Responsibilities

Discipline/Resources	DLR	
Team Leader	Volker Maiwald	RY-SR
DHS	Maximilian Engelsberger	RY-AS
Communication / G/S	Andy Braukhane	RY-SR
Thermal	HoGe Lötze	RY-SK
Power	Waldemar Bauer	RY-SR
Propulsion	Florian Ruhhammer	RY-SR
AOCS	Markus Schlotterer	RY-NR
Configuration	Svenja Stellmann / Stefan Cornelius	RY-SR
Structure (incl. Mechanisms)	Siebo Reershemius / Tom Sprowitz	RY-SR
Cost	Olga Trivailo/ Egbert van de Veen	RY-RT
Mission Analysis	Dominik Quantius	RY-SR
Systems	Hardi Peter/ Dominik Quantius	MPS/ RY-SR
Instruments / Science	Achim Gandorfer / Werner Curdt/ Johann Hirzberger	MPS
CEF	Oliver Romberg	RY-SR
CEF-Software	Daniel Lüdtké	SC-RV
CEF-Support	Gudrun Ziegler, Charles Max, Hubert Moser, Adrienne Ouaf, Martin Kracheel	Uni Lux



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Deutsches Zentrum für Luft und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Institut für Raumfahrtssysteme
Systemanalyse Raumsegment (SARA)

Volker Maiwald

Robert-Hooke-Str. 7
D-28359 Bremen
Telefon 0421 24420-251
Telefax 0421 24420-150

E-Mail mailto: Volker.Maiwald@DLR.de

Internet <http://www.dlr.de/irs/>

Table of Contents

1.	Introduction	10
1.1.	General Science Background	10
1.2.	Concurrent Engineering Approach	12
1.3.	Document Information	15
2.	System	16
2.1.	Mission Objectives	16
2.2.	Mission Requirements	16
2.3.	System Requirements	16
2.4.	Baseline Design	17
2.4.1.	Modes of Operation	17
2.5.	To be studied / additional Consideration	19
2.6.	Summary	19
2.6.1.	Mass budget	19
3.	Mission Analysis	22
3.1.	Requirements and Design Drivers	22
3.1.1.	Launcher Requirements	22
3.1.2.	Orbit Requirements	22
3.1.3.	Ground Segment and Operations	23
3.2.	Options and Trades	25
3.3.	Summary	26
4.	Instruments	27
4.1.	Instrument description	27
4.1.1.	Instrument Parameters	28
4.1.2.	Open Issues and further trade-offs	30
4.2.	Summary	30
5.	Data Handling System	31
5.1.	Assumptions	31
5.2.	Data Volume Requirements	31
5.3.	Conclusions for the C&DG Throughput	32
5.4.	Baseline Design	32
5.4.1.	Functional Partitioning on both Spacecraft	32
5.4.2.	Hardware Specification Proposal	33
5.4.3.	Software Architecture Proposal	34
5.4.4.	List of Equipment Mass and Power Budget	36
5.4.5.	Ground Station Data Handling	36
5.5.	Options and Trades	37
5.5.1.	Fault Protection	37
5.5.2.	Software Development Tools	37
5.6.	Summary	37
6.	Communication	39
6.1.	Requirements and Design Drivers (or Assumptions)	39
6.2.	Ground Station Contacts	40
6.3.	Options and Trades	40
6.4.	Baseline Design	41
6.4.1.	Payload data downlink (X-band)	41
6.4.2.	TT&C up-/downlinks (S-band)	42

6.4.3.	Intersatellite communication (UHF-band).....	42
6.5.	Link Budget.....	42
6.6.	List of Equipment Mass and Power Budget.....	44
6.6.1.	Mass Budgets.....	44
6.6.2.	Power Budgets.....	45
6.7.	To be studied / additional Consideration.....	45
6.7.1.	Optional Ka-band P/L data downlink.....	45
6.7.2.	Housekeeping data transmission increase.....	46
6.7.3.	Further options.....	46
6.7.4.	Open issues.....	46
6.8.	Summary.....	47
7.	Power.....	48
7.1.	Requirements and Design Drivers.....	48
7.2.	Modes of Operation.....	48
7.3.	Baseline Design.....	49
7.3.1.	Primary Power Design (S/G).....	50
7.3.2.	Secondary Power Design (Batteries).....	51
7.3.3.	List of Equipment and Mass Budget.....	52
7.3.4.	Power Budget.....	55
7.4.	To be studied / additional Consideration.....	56
7.5.	Summary.....	56
8.	Thermal.....	57
8.1.	Requirements and Design Drivers (Assumptions).....	57
8.2.	Options and Trades.....	57
8.3.	Baseline Design.....	58
8.3.1.	List of Equipment Mass and Power Budget.....	61
8.4.	To be studied / additional Consideration.....	62
8.5.	Summary.....	63
9.	Attitude and Orbit Control System.....	64
9.1.	Introduction.....	64
9.2.	Pointing Requirements.....	64
9.3.	Requirements and Design Drivers.....	64
9.3.1.	List of Equipment Mass and Power Budget.....	65
9.3.2.	Component Locations on SolmeX.....	66
9.3.3.	Performance Specifications.....	67
9.3.4.	Mass and Power Budget.....	67
9.3.5.	Disturbance Torques.....	67
9.3.6.	Actuator Performance.....	68
9.4.	Reliability and Redundancy/ Risk.....	68
9.5.	To be studied / additional Consideration.....	68
9.6.	Summary.....	69
10.	Configuration.....	71
10.1.	Requirements and Design Drivers.....	71
10.2.	Baseline Design.....	72
10.2.1.	Coronagraph Spacecraft.....	72
10.2.2.	Occulter Spacecraft.....	72
10.3.	To be studied / additional Consideration.....	75
10.4.	Summary.....	76

11.	Structure incl. Mechanisms	77
11.1.	Requirements and Design Drivers.....	77
11.2.	Options and Trades	78
11.3.	Baseline Design	79
11.3.1.	List of Equipment Mass Budget.....	79
11.4.	To be studied / additional Consideration	80
11.5.	Summary.....	80
12.	Propulsion.....	81
12.1.	Requirements and Design Drivers.....	81
12.2.	Options and Trades	81
12.3.	Baseline Design	82
12.3.1.	Thrusters.....	82
12.3.2.	Propellant Tanks.....	82
12.3.3.	Pressurisation System.....	83
12.3.4.	Piping Plan.....	83
12.3.5.	List of Equipment Mass and Power Budget	84
12.4.	Additional Consideration	85
12.5.	Summary.....	86
13.	Cost Analysis	87
13.1.	Introduction	87
13.2.	Cost Estimation Methodology Theory.....	87
13.2.1.	Small Satellite Cost Model (SSCM2007).....	89
13.2.2.	Cost Estimate Relationships (CERs).....	90
13.3.	SSCM Application to SolmeX	91
13.4.	Requirements	92
13.5.	Assumptions	92
13.6.	Cost Distribution	94
13.6.1.	Development and Satellite Industrial Activity Costs	96
13.6.2.	Launch Services	101
13.6.3.	Operation	101
13.7.	Summary.....	102
14.	CEF-Support.....	104
15.	Acronyms.....	106
16.	References	110

List of Figures

Figure 1-1: The Concurrent Design approach compared to projections of conventional design process.	13
Figure 1-2: Concurrent Engineering Facility main room (lefthand) and working during CE-study phase (righthand) at DLR Bremen	14
Figure 2-1: Size and geometry of the occulter's umbra on the CUSP and VIRCOR instruments.	18
Figure 2-2: Size and geometry of the Occulter spacecraft relative to the umbra on the Coronagraph spacecraft.	18
Figure 2-3: Mass budget of the Coronagraph S/C.	20
Figure 2-4: Mass budget of the Occulter S/C.	21
Figure 3-1: Lissajous orbit in the Rotating Libration Point frame.	23
Figure 3-2: Distribution of ESA ground stations.	24
Figure 3-3: Contact times of possible ground stations (SolmeX crossing ecliptic plane).	24
Figure 3-4: Lissajous orbit around L_1 in the RLP frame simulated with STK.	24
Figure 5-1: Functional partitioning on both spacecraft.	33
Figure 5-2: Software architecture block diagram.	34
Figure 6-1: Distances between the spacecraft(s), Earth and the Sun.	39
Figure 6-2: Communication links.	41
Figure 6-3: X-band and S-band link budgets (downlink).	43
Figure 7-1: Modes of operation as used for the layout of the power system.	48
Figure 7-2: Baseline design of the Power subsystem.	49
Figure 7-3: Baseline design of the Power subsystem.	52
Figure 8-1: S/C baseline design.	57
Figure 8-2: Principal TCS design.	59
Figure 8-3: Both S/C with possible radiator areas (red coloured).	59
Figure 8-4: Possible radiator areas (red coloured) with deployed radiator solar arrays.	60
Figure 8-5: Possible radiator areas (red coloured) on the Occulter S/C.	60
Figure 10-1: CUSP and VIRCOR position requirement.	72
Figure 10-2: Coronagraph S/C baseline design.	73
Figure 10-3: Occulter S/C baseline design	74
Figure 10-4: Occulter S/C configuration side 1	74
Figure 10-5: Occulter S/C configuration side 2	75
Figure 10-6: Coronagraph S/C configuration for thruster, solar panels and radiators	75
Figure 10-7: Occulter S/C configuration for radiator	76
Figure 11-1: S/C - Launcher configuration and consequential requirements.	77
Figure 11-2: Coronagraph S/C structure options.	78
Figure 11-3: Baseline design - Coronagraph S/C structure	79
Figure 12-1: The two thruster types used for the SolmeX mission: a) CHT 10 by EADS Astrium b) Proportional Micro Thruster by Bradford	82
Figure 12-2: The piping plan for the Occulter S/C's Attitude Control System.	83
Figure 12-3: The piping plan for the Coronagraph S/C's 10N thrusters main engine.	84
Figure 13-1: Cost estimation according to program phase	88
Figure 13-2: Cost Cost Estimation Relationship (CER) – Power Subsystem.	89
Figure 13-3: Example of a mathematical formula of a Cost Estimating Relationship (CER).	90
Figure 13-4: Parametric estimating procedure for calculating satellite cost by using several CERs. Left hand side: Weighted-average algorithm for final cost estimate.	91

List of Tables

Table 2-1: Modes of Operation for SolmeX.	17
Table 3-1: Trajectory sequence.	22
Table 3-2: Tradeoff between different orbit types.	26
Table 4-1: Instrument parameters of SolmeX' payload.....	29
Table 5-1: Assumptions regarding data transfer.....	31
Table 5-2: Payload datarates of SolmeX.	31
Table 5-3: Housekeeping datarates of SolmeX.	32
Table 5-4: Sum of data to be stored and transferred.	32
Table 5-5: Payload link scenario.	32
Table 5-6: Intersatellite link scenario.....	32
Table 5-7: Power consumption estimate of the DHS.	33
Table 5-8: Estimate of physical dimensions of the OBC box.	33
Table 5-9: Mass budget for the Data Handling system.....	36
Table 5-10: Power budget for the Data Handling system.	36
Table 5-11: Data archive requirements on the ground.	36
Table 6-1: ESA ground stations [RD 2].	40
Table 6-2: Different options for the communication design.	40
Table 6-3: Mass budget for the communication subsystem of the Coronagraph S/C.	44
Table 6-4: Mass budget for the communication subsystem of the Occulter S/C.	44
Table 6-5: Power budget for the communication subsystem of the Coronagraph S/C.....	45
Table 6-6: Power budget for the communication subsystem of the Occulter S/C.	45
Table 7-1: Power requirements w.r.t. the Coronagraph S/C.....	50
Table 7-2: Power requirements w.r.t. the Occulter S/C.	51
Table 7-3: Battery layout of the Coronagraph S/C.....	51
Table 7-4: Battery layout of the Occulter S/C.	52
Table 7-5: Mass budget of power subsystem of the Coronagraph S/C.	53
Table 7-6: Mass budget of power subsystem of the Occulter S/C.....	53
Table 7-7: Equipment list of power subsystem of the Coronagraph S/C.....	54
Table 7-8: Equipment list of power subsystem of the Occulter S/C.....	54
Table 7-9: Power budget of the Coronagraph S/C.....	55
Table 7-10: Power budget of the Occulter S/C.	55
Table 8-1: TCS mass budget of the Coronagraph S/C.....	61
Table 8-2: TCS mass budget of the Occulter S/C.....	61
Table 8-3: TCS power budget of the Coronagraph S/C.....	62
Table 8-4: TCS power budget of the Occulter S/C.	62
Table 9-1: AOCS mass budget of the Coronagraph S/C.	65
Table 9-2: AOCS mass budget of the Occulter S/C.....	65
Table 9-3: AOCS power budget of the Coronagraph S/C.....	66
Table 9-4: AOCS power budget of the Occulter S/C.	66
Table 9-5: Disturbances occurring during SolmeX.	68
Table 11-1: Structure mass budget for the Coronagraph S/C.	79
Table 11-2: Structure mass budget for the Occulter S/C.....	80
Table 12-1: The required ΔV s for the two spacecraft of the SolmeX mission, the Coronagraph S/C (El 1) and the Occulter (El 2).	81

Table 12-2: Summary of the properties of the thrusters used for SolmeX' two spacecraft.	82
Table 12-3: Mass budget for the Coronagraph S/C's propulsion system.	84
Table 12-4: Mass budget for the Occulter S/C's propulsion system.	85
Table 12-5: Power budget for the Coronagraph S/C's propulsion system.	85
Table 12-6: Power budget for the Occulter S/C's propulsion system.	85
Table 13-1: ESA Cost at Completion reference building blocks.	92
Table 13-2: SolmeX mission cost estimate breakdown.	94
Table 13-3: Coronagraph S/C System and Subsystem Cost Breakdown.	95
Table 13-4: Occulter S/C System and Subsystem Cost Breakdown.	95
Table 13-5: ESA Cost at Completion reference building blocks.	95
Table 13-6: SolmeX compared to ESA Cost at Completion reference building blocks.	96
Table 13-7: Technical Input Parameters for the Solmex Coronagraph S/C.	97
Table 13-8: Technical Input Parameters for the Solmex Occulter S/C.	98
Table 13-9: Overview of SolmeX Coronagraph S/C input data with respect to SSCM range of values.	99
Table 13-10: Overview of SolmeX Occulter S/C input data with respect to SSCM range of values.	99
Table 13-11: Cost estimation for SolmeX Coronagraph S/C [k€, FY2010].	100
Table 13-12: Cost estimation for SolmeX Occulter S/C [k€, FY2010].	100
Table 13-13: Cost Distributions for SolmeX Coronagraph S/C.	102
Table 13-14: Cost Distributions for SolmeX Occulter S/C.	103
Table 13-15: Summary of the SolmeX mission costs.	103

1. Introduction

The solar corona's structure, dynamics and energy condition are primarily influenced by the Sun's magnetic field. Currently, measurements of the magnetic field only occur at solar surface and not within the corona itself. This lack of measurements is intended to be erased by the SolmeX-mission (*Solar magnetism eXplorer*). The scientific objectives of this mission are the mapping of the magnetic field in the solar transition region and the corona and also to determine the origin and evolution of the magnetic field and investigate its interaction with the heliospheric plasma, effects that are responsible for coronal mass ejections (CMEs) and solar flares.

SolmeX will carry five instruments to observe the solar disk and also the corona region above the solar limb. The latter uses an occulter to block out the solar radiation and illumination for an undisturbed view of the solar corona. The observational spectrum range includes visible, infrared, ultraviolet and extreme ultraviolet wavelengths.

SolmeX consists of two spacecraft flying in a precise formation behind each other with regard to the Sun. The smaller spacecraft serves as occulter for the two limb viewing instruments of the main spacecraft. The larger spacecraft tasks are the observation of the mission relevant solar regions and also the data transfer to Earth [RD 1].

The CE study for SolmeX took place from 1st to 4th November 2010 in the Concurrent Engineering Facility of the DLR Bremen. The instrument domain was represented by members of the Max Planck Institute for Solar System Research in Lindau, DLR staff took over the remaining positions of the study and also observed the process with regard to software development (SC-RV). In addition five scientists from the University of Luxemburg took part in the study for scientific observation of the Concurrent Engineering process.

The results of the study and the SolmeX mission are intended to enter into the ESA Cosmic Vision Call for M-class missions in December 2010.

1.1. General Science Background

The structure and dynamics of the outer solar atmosphere is dominated by the magnetic field. It is the main scientific goal of the proposed mission to provide the first complete set of measurements of the magnetic field from the upper chromosphere to the outer corona through remote-sensing techniques over a multitude of spatial and temporal scales.

Our current lack of measurements of the coronal magnetic field is a major drawback for further progress in understanding the solar upper atmosphere. The magnetic field structures and drives the plasma in the upper atmosphere and controls the conversion of magnetic energy into thermal and kinetic energy. Such disruptions can lead to the ejection of magnetic flux and plasma into interplanetary space disturbing large parts of the heliosphere, including the environment of Earth. Transferring and comparing the results for the solar upper atmosphere to younger stars will improve our knowledge of the magnetic field in the surroundings of these objects hosting young planets in their formation stage.

The scientific goals are closely related to two of the four main questions of the *Cosmic Vision* plan, namely “how does the Solar System work?” and “what are the conditions for planet formation and the emergence of life?”

In particular, SolmeX will address major open questions concerning the physics of the Sun and the heliosphere, namely

- What determines the magnetic structure of the solar upper atmosphere?
- What is the nature of the changes of the magnetic field over the solar cycle?
- What drives large-scale coronal disruptions such as flares and coronal mass ejections?
- How do magnetic processes drive the dynamics and heating of the outer atmosphere?
- How is the magnetic field coupling the whole solar atmosphere, from the photosphere to the outer corona?

The instrumentation envisaged for SolmeX will outperform current space instrumentation in terms of spatial, temporal and spectral resolution, but more importantly, it will add the unique capability to investigate the state of the polarization of the Sun's upper atmospheric radiation. This will open a new window for studies of the magnetic field in the upper solar atmosphere. Through the Zeeman effect as well as through quantum mechanical interference, the Hanle effect, the magnetic field changes the polarization of the incident radiation. Combining the polarimetric measurements with advanced modeling of solar features including line formation will allow the magnitude and direction of the magnetic field to be inferred. This will (1) constrain extrapolations of surface magnetic fields; (2) provide a test for magnetohydrodynamic models of the interaction of magnetic field and plasma in the upper atmosphere; and (3) enable us to directly investigate the conversion of magnetic energy into heat and mass flows.

Polarimetric measurements as they will be performed by SolmeX are desperately needed to overcome limitations due to our fragmentary knowledge of the magnetic field in the upper atmosphere.

To achieve these goals, SolmeX will be equipped with coronagraphic instruments for off-limb observations in the ultraviolet (UV) and the infrared (IR) as well as with instruments for on-disk observations in the UV and extreme ultraviolet (EUV). Two UV spectro-polarimeters, one for on-disk and one for off-limb observations, will mainly utilize the Hanle effect for the deduction

of magnetic fields and operate in the wavelength range of 90 nm to 200 nm. Likewise the on-disk EUV imaging polarimeter observing coronal emission lines at 17 nm will provide magnetic information through the Hanle effect. The IR imaging spectro-polarimeter will observe the off-limb corona in coronal emission lines near 1 μm affected by the Zeeman effect. The suite will be complemented by a Doppler-magnetograph imager providing information at the base of the corona.

A special demand for the coronagraphic observations is a very sharp shadow from the occulter blocking the light from the Sun's surface. This is needed (1) to minimize the stray light for the delicate polarimetric observations; and (2) to avoid artifacts when observing close to the limb (diffraction patterns). The best performance can be achieved with an external occulter located far from the telescope, i.e. having two spacecraft in formation flight, one serving as the occulter, the other carrying the instruments. Only this can provide a true artificial solar eclipse which is essential to reach the science goals of this mission. The coronagraphic instruments would be inside the shadow of the occulting spacecraft, the on-disk instruments outside.

Overall, SolmeX will provide groundbreaking data, for the first time providing a comprehensive view of the Sun's magnetic field from the chromosphere to the outer corona based on direct measurements. This will be pivotal for our understanding of the structure and dynamics of the solar corona and the impact these processes have on the solar system, and the Earth in particular.

1.2. Concurrent Engineering Approach

To investigate and define the technical concept of the SolmeX a Concurrent Engineering (CE) Study at DLR Bremen has been performed. The CE-study comprised the analysis and the development of all subsystems necessary for SolmeX i.e. configuration, instruments, structure design, thermal, data handling, communication, power, propulsion, AOCS, mission analysis and cost estimation.

The applied Concurrent Engineering (CE) process is based on the optimization of the conventional established design process characterized by centralized and sequential engineering (see Figure 1-1 top). Simultaneous presence of all relevant discipline's specialist within one location and the utilization of a common data handling tool enable efficient communication among the set of integrated subsystems (see Figure 1-1 bottom).

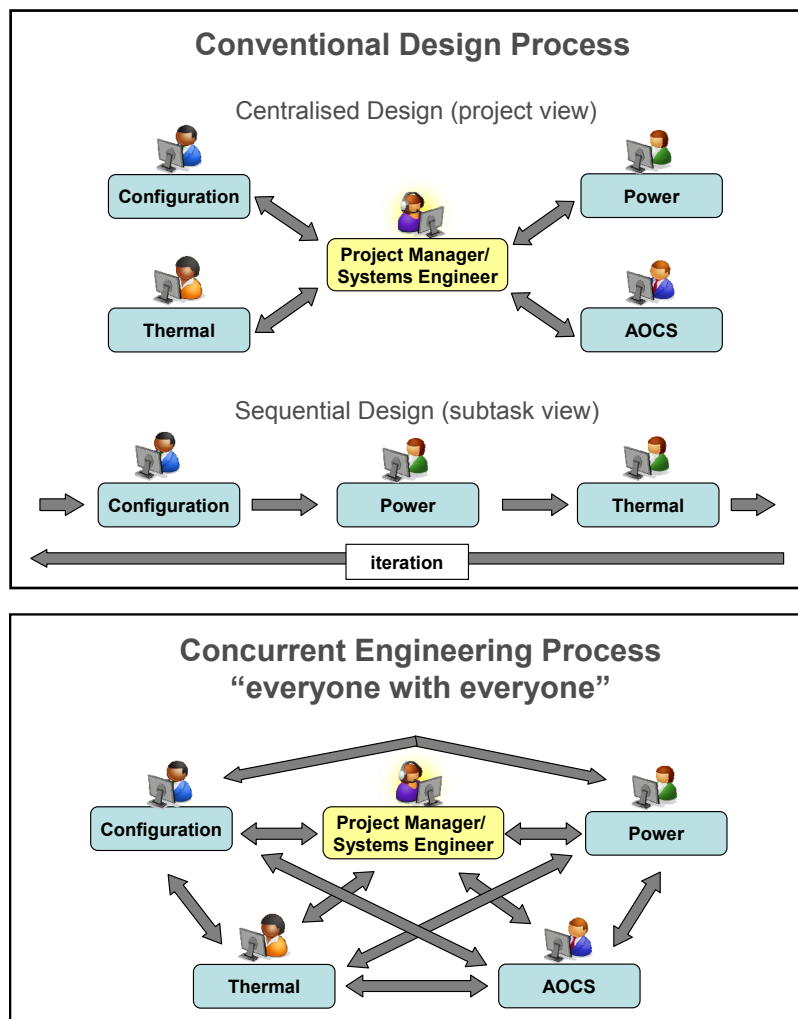


Figure 1-1: The Concurrent Design approach compared to projections of conventional design process.

The CE-Process is based on simultaneous design and has four phases ("IPSP-Approach"):

1. Initiation Phase (starts weeks/months before using the CE-facility):

- Customer (internal group, scientists, industry) contacts CE-team
- CE-team-customer negotiations: expected results definition, needed disciplines

2. Preparation Phase (starts weeks before using CE-facility):

- Definition of mission objectives (with customer)
- Definition of mission and system requirements (with customer)
- Identification and selection of options (max. 3)
- Initial mission analysis (if applicable, e. g. based on STK)
- Final definition and invitation of expert ensemble, agenda definition

3. Study Phase (1- 3 weeks at CE-Facility in site):

- K/O with presentations of study key elements (goals, requirements)
- Starting with first configuration approach and estimation of budgets (mass, power, volume, modes, ...) on subsystem level
- Iterations on subsystem and equipment level in several sessions (2- 4 hours each); trading of several options
- In between offline work: subsystem design in splinter groups
- Final Presentation of all disciplines / subsystems

4. Post Processing Phase:

- Collecting of Results (each S/S provides Input to book captain)
- Evaluation and documentation of results
- Transfer open issues to further project work

The DLR's Concurrent Engineering Facility in Bremen is derived from the Concurrent Design Facility at ESA's ESTEC (European Space Research and Technology Centre), which has already been in operation for more than ten years. Bremen's DLR-CEF has one main working room where the whole design team can assemble and each discipline is supplied with an own working station for calculations and interaction with a special design tool developed by ESTEC. Three screens, one of them interactive, allows display of data in front of the team. Further working positions are provided in the centre of the working area and are usually reserved for customers, PIs, guests and also the team leader and possibly the systems engineer. Two more splinter rooms provide the design team with separated working spaces where sub-groups can meet, discuss and interact in a more concentrated way.

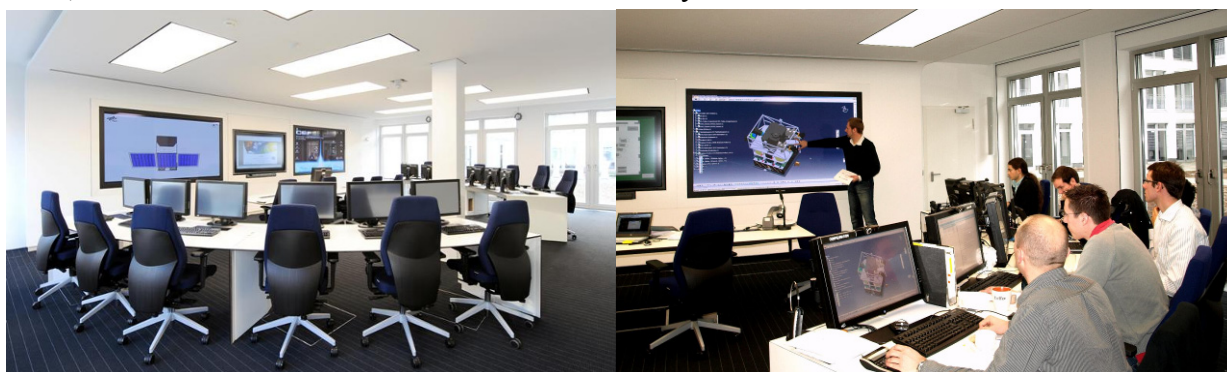


Figure 1-2: Concurrent Engineering Facility main room (lefthand) and working during CE-study phase (righthand) at DLR Bremen

The major advantages of the CE-process are:

- Very high efficiency regarding cost & results of a design activity (Phase 0, A)

- Assembly of the whole design team in one room facilitates direct communication and short data transfer times
- The team members can easily track the design progress, which also increases the project identification
- Ideas and issues can be discussed in groups, which brings in new viewpoints and possible solutions; avoidance and identification of failures and mistakes

1.3. Document Information

This document summarizes the progress and results of the DLR Concurrent Engineering study about the SolmeX mission, which took place from 1st to 4th November 2010 in the Concurrent Engineering Facility of the DLR Institute of Space Systems in Bremen.

The single subsystems or domains as investigated during the study are covered in individual chapters, which explain the study progress, elaborate on decisions and trade offs made during the study and also design optimizations.

2. System

2.1. Mission Objectives

The overall objectives of the SolmeX mission are the mapping of the magnetic field in the corona and transition region of the solar atmosphere and to discover the origin and to determine the evolution of solar magnetism and its interaction with heliospheric plasma. For this purpose, SolmeX will carry five instruments:

Eclipse view

- Visible Light and IR Coronagraph (VIRCOR)
- Coronal UV spectropolarimeter (CUSP)

Non-eclipse view

- Scanning UV spectro-polarimeter (SUSP)
- EUV imaging polarimeter (EIP)
- Chromospheric Magnetism Explorer (ChroME)

2.2. Mission Requirements

In preparation for the CE-study the following mission requirements were defined:

- Uninterrupted observation of the Sun for day long periods is required
- Mission costs (instruments not included) may not exceed 470 Million € (Cosmic Vision M-class budget limit)
- Orbit has to support formation flight stability, alternatives: HEO, GEO, L1
- Soyuz Fregat is the upper limit for a launch vehicle per definition of Cosmic Vision M-class missions and is therefore used as launcher for SolmeX
- Solar disk and solar limb are to be observed during SolmeX

2.3. System Requirements

In order to dimension the spacecraft's subsystems and to fulfill the science constraints the following system requirements were predefined:

- The spacecrafts lifetime is 3 years with another 3 years extension
- To allow corona observation of sufficient quality, the mission has to employ a coronagraph spacecraft (CS) and an occulter spacecraft (OS) flying autonomously in formation with each other

- The distance between the spacecraft needs to be at least 100 m with $\pm 5 \cdot 10^{-2} \%$ accuracy
- Lateral difference in position between the two spacecrafts may not exceed $\pm 5 \cdot 10^{-6} \%$ of the distance
- Roll angle around axis occulter - instrument s/c: < 1 arcmin / 15 min;
pointing accuracy: ± 0.2 arcsec / 20 min
- System mass has to remain < 2.100 kg (launch capability of Soyuz Fregat from Kourou to L_1)
- The design shall be based on Technology Readiness Level (TRL) 5 or higher
- Instrument cleanness has to be ensured (for EUV instruments especially)
- Back-illumination from OS to CS must be mitigated
- Instrument temperature has to be between 17 and 23°C with a stability of 0.1°C during observation

2.4. Baseline Design

The minimalistic equipped Occulter spacecraft will spend a specific designed shadow for the Coronagraph spacecraft that contains all the instruments and main data and communication systems. The caused shadow is sketched in Figure 2-1, whereas the Occulter shape is presented in Figure 2-2.

2.4.1. Modes of Operation

During the course of the study several Modes of Operation have been defined to distinguish between various operational conditions and tasks. The modes were chosen identical for both spacecraft. They are summarized in Table 2-1.

Table 2-1: Modes of Operation for SolmeX.

Mode	Description	Abbreviation	Duration
Launch and Early Operations Mode	Covering launch and commissioning of the spacecraft	LM	1.5 d
Transfer Mode	Orbit transfer to target region, solar array is deployed	TM	14 weeks
Manoeuvre Mode	Change of attitude, rotation and desaturation of reaction wheels, once a day	MM	30 min
Science Mode	All instruments operating, data transfer	ScM	11.5 h
Formation Acquisition Mode	Satellite separation and formation (re)acquisition	FAM	4 h
Safe Mode	Vehicle rescue, standby for all subsystems, only COM, AOCS and DHS are operating	SfM	1.5 d

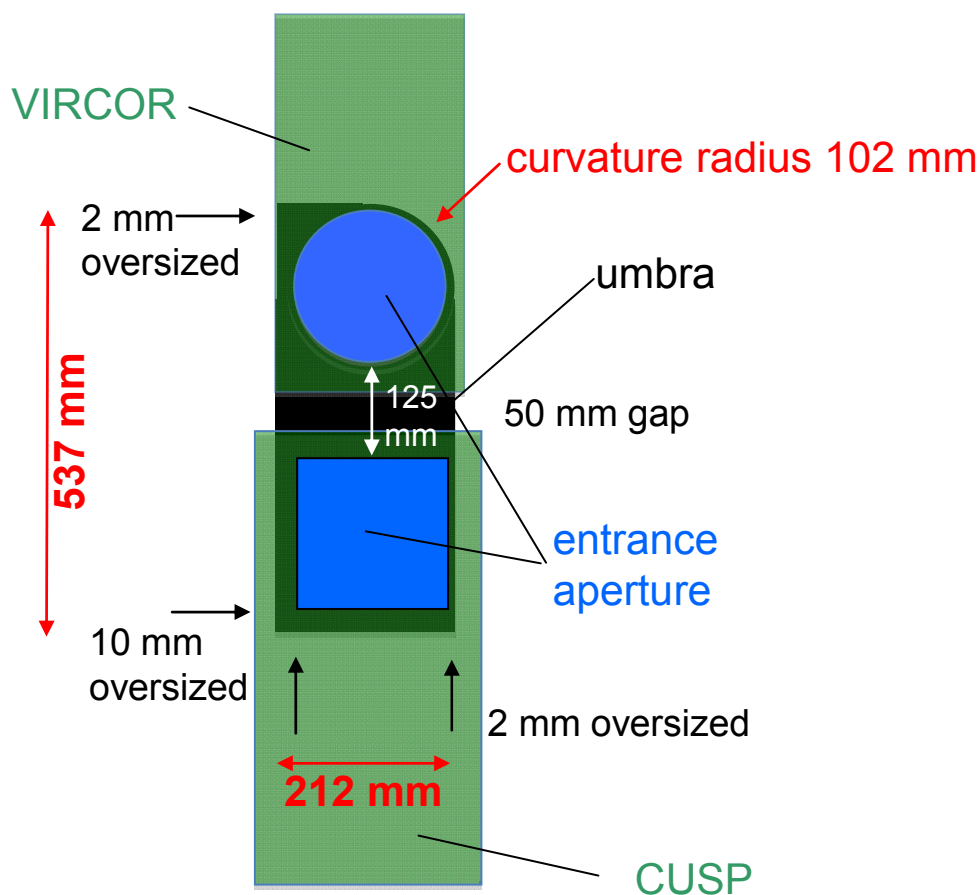


Figure 2-1: Size and geometry of the occulter's umbra on the CUSP and VIRCOR instruments.

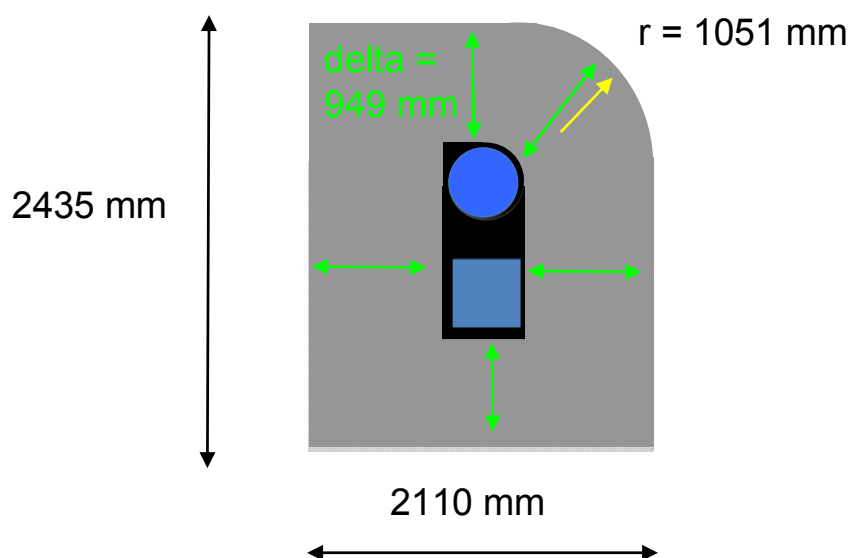


Figure 2-2: Size and geometry of the Occulter spacecraft relative to the umbra on the Coronagraph spacecraft.

2.5. To be studied / additional Consideration

After the CE-study several mission relevant aspects need to be further analyzed. These are:

- Exhaust plume effects on viewing instruments (regarding disturbing observation and regarding damaging effects on optical systems)
- Back illumination from the Occulter S/C to the Coronagraph S/C e.g. due to light emitted by Earth, etc. at L_1
- Currently the thrusters applied for formation keeping have not yet reached TRL 5. Their development (for Proba-3 Mission) has to be monitored and alternatives need to be investigated.

Further considerations, which do not necessarily affect the whole mission feasibility, are listed in the chapters regarding the individual subsystems.

2.6. Summary

SolmeX will consist of two spacecraft. The first one, the Coronagraph spacecraft (CS) (labelled Element 1 during the study) will carry the science payload. The second one, the Occulter spacecraft (OS) (labelled Element 2 during the study) will provide the eclipsed view of the sun for the CS. Mission lifetime is set from 3 years (T) to 6 years (G). The most critical aspect of the design is the accurate formation keeping of the two S/C.

2.6.1. Mass budget

Figure 2-3 and Figure 2-4 show the mass budget of the two spacecraft, which add together to a total mass of 2,185.2 kg – which is just slightly above the maximum launch mass of 2,100 kg.

Element 1 SolmeX Coronagraph Spacecraft								
				Target Spacecraft Mass at Launch				
				2100,00		kg		
				Below Mass Target by:		635,77 kg		
	Input Mass	Input Margin		Without Margin	Margin		Total	% of Total
			Dry mass contributions		%	kg	kg	
DI	400,00		Structure	400,00 kg	0,00	0,00	400,00	38,18
EL			Thermal Control	29,85 kg	9,59	2,86	32,71	3,12
EL			Communications	18,80 kg	10,00	1,88	20,68	1,97
EL			Data Handling	11,00 kg	10,00	1,10	12,10	1,16
EL			AOCS	73,20 kg	11,15	8,16	81,36	7,77
EL			Propulsion	34,33 kg	18,45	6,33	40,66	3,88
EL			Power	81,30 kg	10,00	8,13	89,43	8,54
EL			Harness	65,95 kg	20,00	13,19	79,14	7,55
EL			Instruments	242,90 kg	20,00	48,58	291,48	27,82
Total Dry(excl.adapter)				957,33			1047,56	kg
System margin (excl.adapter)				20,00 %		209,51		kg
Total Dry with margin (excl.adapter)						1257,07		kg
Other contributions								
Wet mass contributions								
DI	107,16		Propellant	107,16 kg	0,00	0,00	107,16	7,85
Adapter mass (including sep. mech.), kg				100,00 kg	0,00	0,00	100,00	0,07
Total wet mass (excl.adapter)						1364,23		kg
Launch mass (including adapter)						1464,23		kg

Figure 2-3: Mass budget of the Coronagraph S/C.

Element 2 SolmeX Occulter Spacecraft								
Target Spacecraft Mass at Launch							0,00	kg
ABOVE MASS TARGET BY:							-720,97	kg
Input Mass	Input Margin		Dry mass contributions	Without Margin	Margin		Total	% of Total
DI	138,00		Structure	138,00 kg	0,00	0,00	138,00	26,54
EL			Thermal Control	4,65 kg	9,73	0,45	5,10	0,98
EL			Communications	8,80 kg	10,00	0,88	9,68	1,86
EL			Data Handling	11,00 kg	10,00	1,10	12,10	2,33
EL			AOCS	47,12 kg	14,55	6,86	53,98	10,38
EL			Propulsion	131,52 kg	19,45	25,58	157,10	30,21
EL			Power	58,98 kg	10,00	5,90	64,88	12,48
EL			Harness	65,95 kg	20,00	13,19	79,14	15,22
Total Dry(excl.adapter)				466,02			519,97	kg
System margin (excl.adapter)					20,00	%	103,99	kg
Total Dry with margin (excl.adapter)							623,97	kg
Other contributions								
Wet mass contributions								
DI	97,00		Propellant	97,00 kg	0,00	0,00	97,00	13,45
Adapter mass (including sep. mech.), kg				0,00 kg	0,00	0,00	0,00	0,00
Total wet mass (excl.adapter)							720,97	kg
Launch mass (including adapter)							720,97	kg

Figure 2-4: Mass budget of the Occulter S/C.

3. Mission Analysis

3.1. Requirements and Design Drivers

3.1.1. Launcher Requirements

In this study referring to the proposed launch vehicles for the ESA Science Programme in the timeframe of the Call for Missions and compatible with the financial envelope of an M-class mission the Soyuz Fregat was chosen to launch the SolmeX Satellites.

It was assumed that Soyuz Fregat can launch 2,100 kg [RD 2] towards the Lagrange points. Special launch window constraints were neglected due to the fact that the launch will be dedicated and a low Earth parking orbit will be used in order to achieve an optimal transfer injection time and position by the Fregat upper stage. Thus in principle a launch should be possible at any time between 2020 and 2022.

Like shown in the table below (Table 3-1), the combined SolmeX satellites will perform correction manoeuvres during the direct transfer towards the region of the L_1 between Earth and Sun as well as the injection into a Lissajous orbit around L_1 by its own propulsion system.

Table 3-1: Trajectory sequence.

Objective	Duration	Delta-v
Launch with Soyuz to 190 km circular orbit	up to 1,5 days	
Second burn of Fregat upper stage towards L_1		
Separation from upper stage / deployment of solar panels		
Transfer to L_1 (correction maneuvers)	about 14 weeks	5 m/s
Orbit capture around L_1	about 100 days	60 m/s

3.1.2. Orbit Requirements

The primary mission goal is the undisturbed observation of the Sun. Therefore, like for other Sun missions as e.g. SOHO, the Lagrange point between Earth and Sun (L_1) is a suitable target. Libration point orbit characteristics are often discussed with reference to a non-inertial coordinate system called the Rotating Libration Point (RLP) frame. This is an L_1 -centered frame where the X-axis points from L_1 to the Earth-Moon barycenter, the Z-axis points up toward the North Ecliptic Pole (NEP), and the Y-axis completes the right-handed frame, pointing approximately along the direction of Earth's velocity vector.

As first estimation a Lissajous orbit like shown in Figure 3-1 with amplitudes of about 400,000 km was chosen. Besides the demands of a free view to the Sun and the communication ability towards Earth, no further constraints came up during the study.

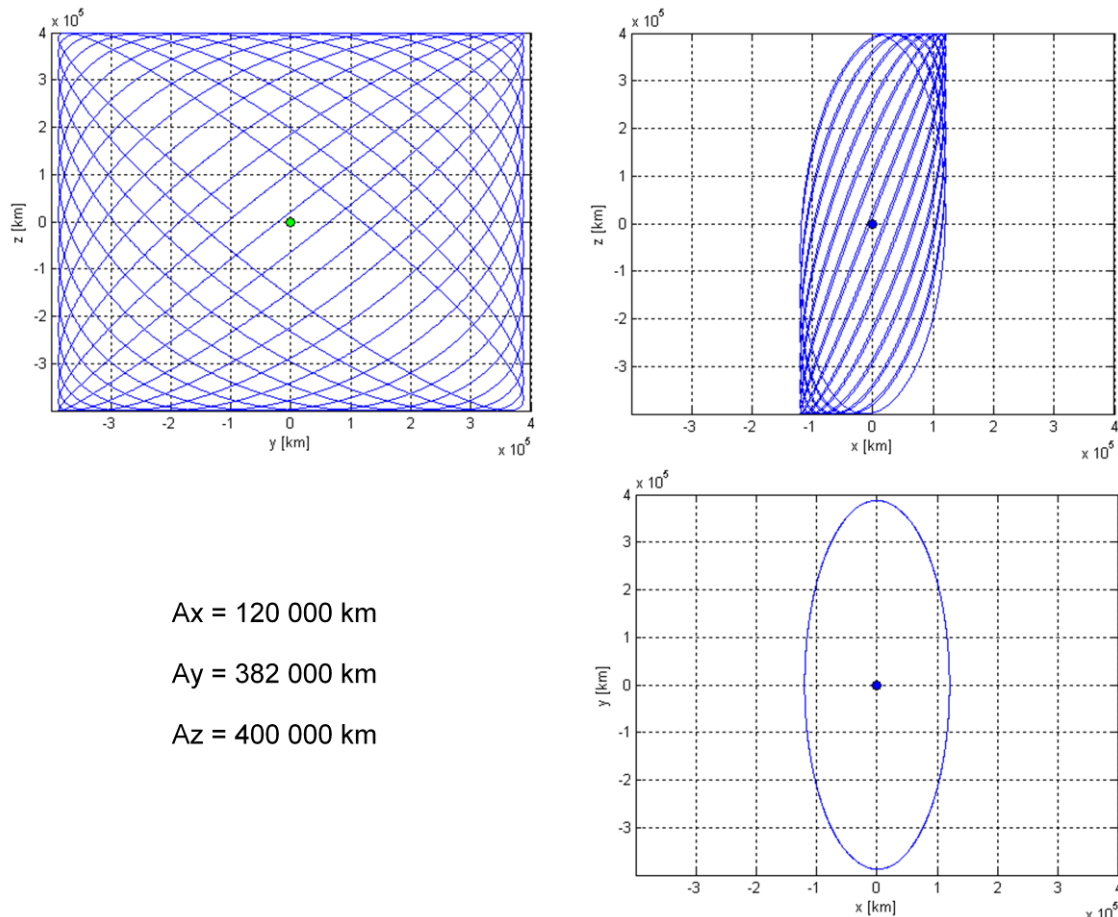


Figure 3-1: Lissajous orbit in the Rotating Libration Point frame.

For orbit keeping 1.67 m/s were foreseen as worst case depending on solar activity every 60 days. This leads to a sum of 60 m/s for each SolmeX satellite for the lifetime of 6 years.

3.1.3. Ground Segment and Operations

Execution of the mission will be in the 2020-2022 timeframe with a lifetime of 3 to 6 years of operation. The standard ESA ground network shall be used e.g. the European Space Operations Centre in Darmstadt and the Science Operations Centre in Villafranca. The communication link design is described in Chapter 6. Possible ground stations and associated contact times are shown in Figure 3-2 and Figure 3-3.

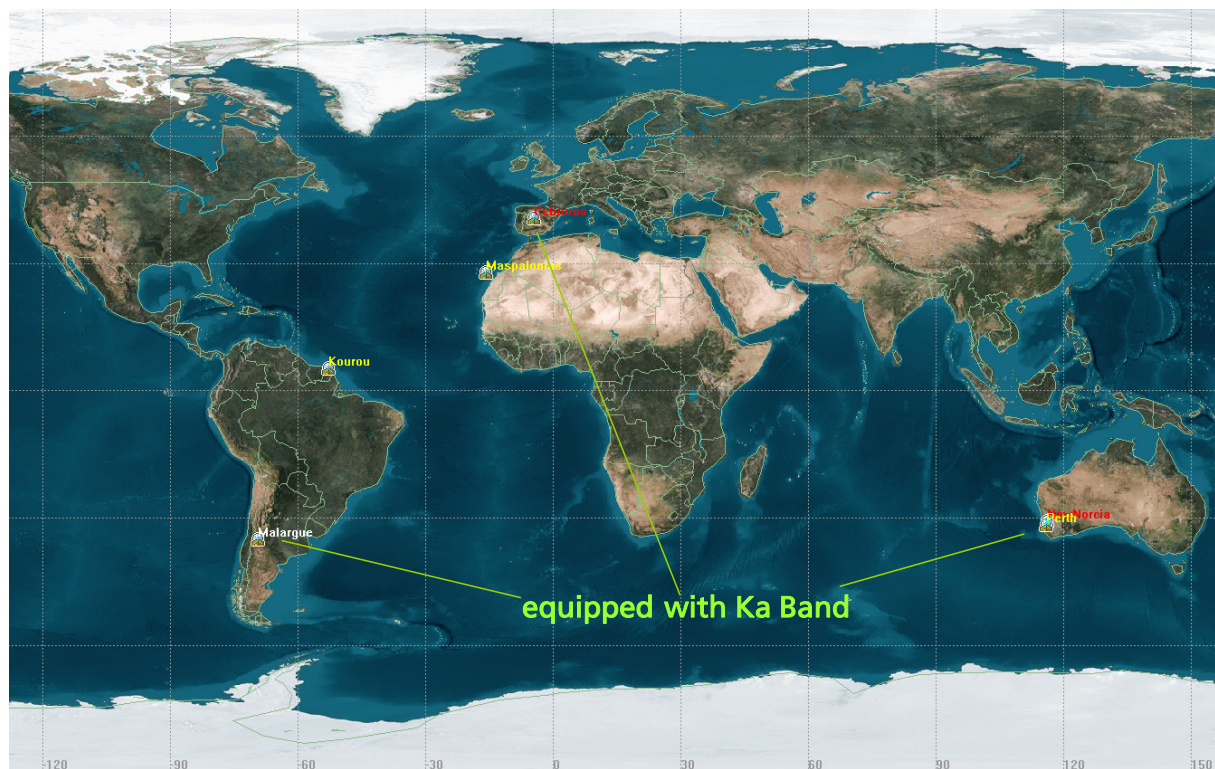


Figure 3-2: Distribution of ESA ground stations.

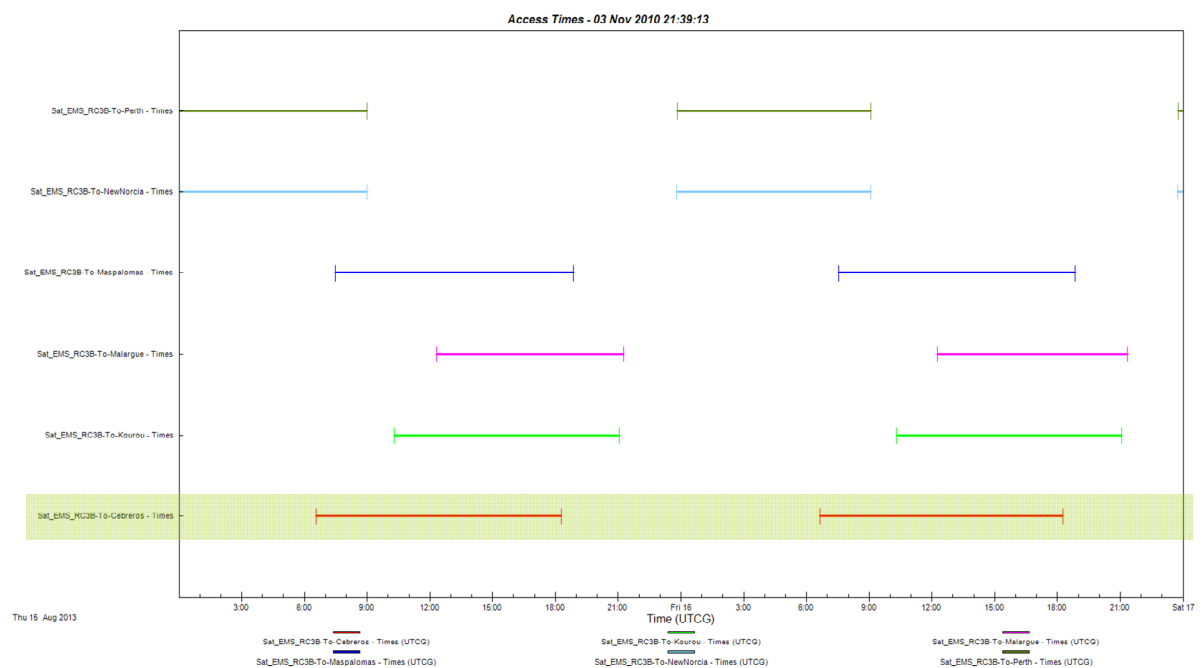


Figure 3-3: Contact times of possible ground stations (SolmeX crossing ecliptic plane).

The ground segment and operations infrastructure shall guarantee the performance of the following tasks:

- Mission preparation covering the operational activities performed to ready the space and ground segment for the SolmeX operational mission
- Mission planning and preparation of the Flight Operations Plan (FOP)
- Spacecraft status monitoring by processing housekeeping data
- Spacecraft control based on monitoring the FOP
- Orbit and attitude determination and control using tracking data and processing attitude and position sensor data and implementing orbit and attitude manoeuvres for formation flying to assure mission success
- On board software maintenance

3.2. Options and Trades

The orbit type and shape around the L_1 is variable. On one hand the variation of the orbit amplitudes leads into delta-v savings for orbit injection and orbit keeping the higher the amplitudes are chosen [RD 3]:

- $A_y=A_z=100\,000\text{ km}$ requires about 180 m/s delta-v for insertion
- $A_y=A_z=400\,000\text{ km}$ requires about 60 m/s delta-v for insertion
- $A_y=A_z=500\,000\text{ km}$ requires about 45 m/s delta-v for insertion

Here the limit is given by the gimbal angle of the antenna dish towards Earth while the instruments are still pointed to the Sun.

On the other hand a variation of the orbit shape allows a Solar Exclusion Zone (SEZ) using a Halo type orbit instead of a Lissajous orbit. Then the spacecraft can skirt the SEZ for the sake of avoiding solar interference with communications.

During study preparation it was decided to take the approach of the Lagrange point as baseline scenario. But also a geostationary (GEO) or a high elliptical orbit (HEO) around Earth could be a possible target for the SolmeX mission. In Table 3-2 a comparison between those orbits is worked out.

Table 3-2: Tradeoff between different orbit types.

	Eclipse Times	Attitude	Thermal	Data Rate	Contact Times	Disturbing Forces
GEO/HEO	possible	complex	varying	high	medium	high
L1	none	simple	constant	low	high	low

3.3. Summary

For Sun observation a mission towards the Lagrange point L_1 is an already proven target. For the SolmeX mission it was assumed, that the Soyuz Fregat launcher will deliver the satellite package towards L_1 . Correction maneuvers during the transfer to L_1 and the orbit injection will be performed by the spacecrafts propulsion system (Delta-V: 65 m/s). As soon as the final Lissajous orbit is achieved the two spacecrafts will separate from each other in order to perform very precise formation flying in 200 m distance. For orbit keeping during the six years long operational period a total delta-v of 60 m/s for each spacecraft is assumed. The main communication link will be overtaken by the Coronagraph spacecraft with the standard ESA Ground segment.

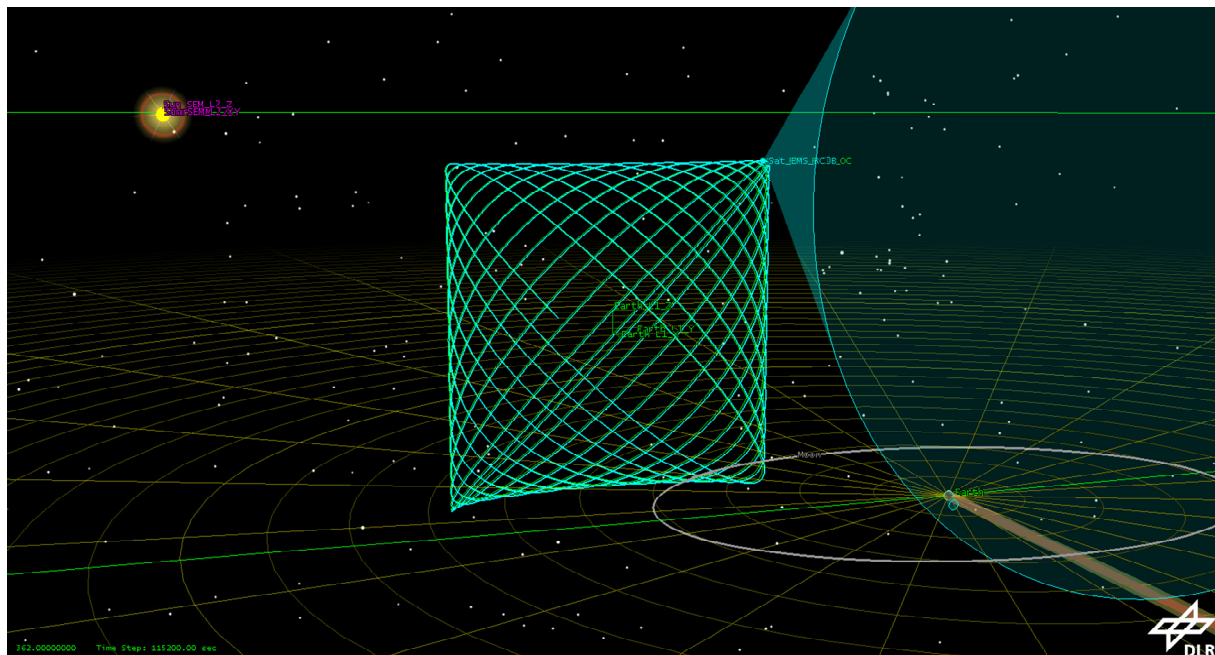


Figure 3-4: Lissajous orbit around L_1 in the RLP frame simulated with STK.

4. Instruments

SolmeX is an ambitious multi-spacecraft observatory. The requirements for the coronagraphic observations call for an external occulter that is far removed from the instruments, too far to be built using a long boom. This requires using a second spacecraft in formation flight to occult the solar disk and by this producing a true solar eclipse. The technology requirements for such a formation flight are demanding, but the progress of Proba3, currently under study by ESA in Phase B until end of 2011, demonstrates the feasibility of such a formation flight. In contrast to Proba3 we envision an halo-orbit around L_1 of the Sun-Earth system, which would allow for more relaxed constraints on the formation-flying metrology.

The instruments for SolmeX build on the heritage of existing spectroscopic and imaging instruments with the added capability to investigate also the polarization state of the incoming photons. As in general the incoming light is polarized by 0.1% to 10%, the instruments envisaged for SolmeX have to have larger light collecting areas and a higher throughput than previous instrumentation, in order to acquire the required signal-to-noise ratio and polarimetric accuracy. When observing in non-polarimetric mode, this implies that the instruments proposed here will outperform the previous ones in terms of spatial and temporal resolution.

4.1. Instrument description

The instruments as proposed here have been designed by an international consortium including institutes from Europe and the USA with high experience in the development of space instrumentation.

The ***coronal UV spectro-polarimeter*** is a coronagraphic instrument designed to measure the resonantly scattered light of the corona as seen in the lines of the Lyman series of hydrogen and in the O IV doublet at 103.2 nm and 103.7 nm. It is based in the heritage of UVCS on SOHO with a similar measurement principle, but now including a polarimetric units based on reflective optics to investigate the linear polarization. These measurements are complementary to the IR coronagraph. The latter shows the magnetic field in million K hot individual structures in the corona, e.g., coronal loops as seen above the limb. The emphasis for the UV coronagraphic instrument is on the large-scale structures that are seen in resonantly scattered light, such as large helmet streamer complexes or the boundaries of coronal holes. The lead for this instrument is with INAF-Torino in Italy.

The ***visible light and infrared coronagraph*** is based on heritage from the coronagraphs flown on SOHO and STEREO and builds on a measurement concept proven by the Coronal Multi-channel Polarimeter (CoMP). It is a classical refractive coronagraph with an external occulter

employing a Lyot filter and a polarizer unit to measure linear and circular polarization with an accuracy of 10^{-4} . This will provide maps of the coronal magnetic field above the limb. The K-coronal channel of this instrument will show the corona as seen in a solar eclipse with unprecedented detail at a spatial resolution of up to 0.5 arcsec. This instrument is proposed by an US-led consortium from NRL, GSFC and HAO.

The *scanning UV spectro-polarimeter* is designed preliminarily for on-disk observations investing the magnetic field structure of the transition region into the corona. It will span a wavelength range from Ly-alpha of hydrogen at 121 nm to the C IV doublet near 155 nm. It build on heritage of UV spectrometers such as SUMER on SOHO and EIS on Hinode, but in addition to these previous instruments is equipped with a refractive polarization unit. This allows to investigate the linear and the circular polarization in Ly-alpha and C IV down to 10^{-3} polarimetric accuracy. Using the Hanle and the Zeeman effects, respectively, this allows to infer the magnetic field in the formation regions of these lines. The proposal for this instrument is led by the Max-Planck-Institute for Solar System Research (MPS), Germany.

The suite of coronal instruments is completed by an *EUV imaging polarimeter*. This instrument will provide images of the type of EIT or TRACE, only in one pass band but including information on the polarization state. Designed for high throughput the multi-layer instrument will use a reflecting polarizer to record also linear polarization at a level of 10^{-3} . The main line in the passband in a Fe X line at 17.4 nm which is linearly polarized and provides diagnostics for the magnetic field. The instrument will not only show the coronal loop-dominates structure of the 10^6 K corona, but will also allow to directly investigate e.g. the direction of the magnetic field in comparison to the structures visible in EUV light. The instrument is based on the heritage of EIT on SOHO and SWAP on Proba2 and builds on the European experience in building multi-layer optics. The lead for this instrument is with Rutherford Appleton Laboratory (RAL), United Kingdom.

For the investigation of the base of the corona a *Chromospheric magnetism explorer* is proposed to study the magnetic field, flows and structure of the chromosphere through the Mg II k line. A device based on a Fabry-Perot-Instrument with a polarizing unit allows to follow the magnetic field structure at the base of the corona and is therefore a crucial instrument to understand the magnetic connection throughout the solar atmosphere. The high-reaching chromospheric structures to be seen above the limb with this instrument will provide a link to the coronagraphic observations. The instrument builds on heritage of the imaging polarimeter ImaX flown on the ballon-bourne mission Sunrise under near-space conditions. The efforts for this instrument are led by the Instituto de Astrofisica de Canarias (IAC), Spain.

4.1.1. Instrument Parameters

Table 4-1 summarizes the instrument parameters of SolmeX' science payload as used during the study.

Table 4-1: Instrument parameters of SolmeX' payload.

	<i>off-limb</i>		<i>on-disk</i>		
instrument specifications	CUSP coronagraphic UV spectro- polarimeter	VIRCOR visible light & IR coronagraph	EIP EUV imaging polarimeter	SUSP Scanning UV spectro- polarimeter	ChroME Chromospheric Magnetism Explorer
spectral lines or band	Ly-a, b, g O IV (103 nm)	Fe XIII 1.07 nm vis: ~ 400 nm	Fe X (17.4 nm)	120nm–160 nm incl, Ly-a, C IV	Mg II (279 nm) Fe I (525 nm)
detector size: [pxl]	2x 1024 ² photon counting	IR: 1024 ² vis: 4096 ²	4096 ²	3x 2048 ² photon counting	Mg II: 2048 ² Fe I: 1024 ²
spatial resolution	5"	IR: 2.3"/pxl vis: 1.2"/pxl	0.5"/pxl	2"/spat.pxl	Mg: 0.15"/pxl Fe: 0.3"/pxl
field of view	slit: 10" x 0.4° raster:0.4°x0.4°	IR: 0.6°x0.6° vis: 1.3°x1.3°	0.6°x0.6°	slit: 1",2"x300" raster:300"x300"	307"x307"
Spectral resolution	6.6 pm per spectr. pxl	IR: 0.2 nm vis: broad band	0.4 nm FWHM band	6.6 pm per spectr. pxl	Mg: 5 pm Fe: 9 pm
polarimetric accuracy	10 ⁻² (linear)	10 ⁻⁴ (linear & circul.)	10 ⁻³ (linear)	10 ⁻³ (linear & circul.)	10 ⁻³ (linear & circul.)
exposure times	1 s – 7 h		10 s (n-p) 10 min (pol)	<1 s (n-p) 1s–3 min (pol)	5 s
data rate	150 kbit/s	300 kbit/s	550 kbit/s	300 kbit/s	700 kbit/s
aperture	25 x 30 cm ²	□ 20 cm	□ 28 cm	15 x 10 cm ²	□ 25 cm
dimension cm ³	180 x 60 x 30	180 x 50 x 25	100 x 30 x 30	160 x 50 x 40	150 x 45 x 50
mass	70 kg	60 kg	40 kg	68 kg	52 kg
power	30 W	50 W	50 W	25 W	55 W
absolute x-y pointing roll	5' 15'	2' 5'	0.5'	2' 1'	
x-y pointing stability roll	1" / 15 min 1' / 15 min	1" / 3 min 1' / 3 min	0.2" / 20 min	1" / 15 min 1' / 15 min	uses internal stabilization

4.1.2. Open Issues and further trade-offs

The instruments build on heritage mainly from SOHO instruments. The major step forward is the implementation of devices to investigate the state of polarization of the light. The technique for these polarimetric devices is well studied. Therefore the risk of the instruments can be considered low.

Individual components that need further investigation are especially the detectors, and here especially for the on-disk UV spectrograph. To ensure the required polarimetric sensitivity the detector has to be a photon counting unit. Comparisons with the SUMER detector on SOHO show that the detector performs well, however it has to be investigated if this is also true for the higher photon fluxes expected for the SolmeX instrument with its larger aperture.

For the chromospheric instrument is employs a Fabry Perot interferometer (FPI) for spectroscopic imaging. Such devices operating at the short wavelengths (280 nm) have not yet been flown in space, but the technique is quite similar to devices in the visible, which have been successfully flown e.g. on Lasco/SOHO.

Another open issue is the polarimetric imaging in the EUV. The polarimetric sensitivity has to be about 0.001, which implies a photometric accuracy of the same order of three successive images. The proposed design used a rotating focal plane package, where the detector is rotation together with a 45° polarizing mirror around the optical axis. This puts high demand on the mechanical accuracy and the calibration of the detector.

4.2. Summary

SolmeX will carry five science instruments of which two need an occulted view to the Sun, for off-limb observations. The remaining three instruments will directly view the solar disk. Observations will take place in the visible, infrared, ultraviolet and extreme ultraviolet ranges.

The scientific objectives of this mission are the mapping of the magnetic field in the solar transition region and the corona and also to determine the origin and evolution of the magnetic field and investigate its interaction with the heliospheric plasma, effects that are responsible for coronal mass ejections (CMEs) and solar flares.

5. Data Handling System

5.1. Assumptions

Some assumptions were made regarding the percentage of the Housekeeping and AOCS data, which will be transferred to ground, however it is unlikely that all of the Housekeeping and AOCS data will need to be transferred. In contrast to that the DHS was designed to allow complete transfer of all the scientific (payload) data. Also during the study an estimate was set up about how long the acquired data could be stored onboard both satellites and how long the contact time to ground has to be per day for ensuring successful transfer of all the created data.

Table 5-1 summarizes the assumptions made for the calculations regarding the Data Handling System.

Table 5-1: Assumptions regarding data transfer.

Percentage of the Housekeeping/AOCS data which is taken for ground-transfer	5.00%
Percentage of the payload data which is taken for ground-transfer	100.00%
Derivation time of the acquired data in hours	24
Duration of contact to ground per day in hours	8

5.2. Data Volume Requirements

Table 5-2 and Table 5-3 show the datarates of the payload instruments and of the Housekeeping/AOCS subsystems. The payload datarates are only for the Coronagraph Spacecraft because the Occulter S/C does not carry any P/L at this time.

Table 5-2: Payload datarates of SolmeX.

Name	Kbit/s	Gbit/day	GB/day
VIRCOR (Visible light & IR coronagraph) - imaging spectropolarimeter	300	24.72	3.09
CUSP (Coronal UV spectropolarimeter) – slit spectro-polarimeter	150	12.36	1.54
SUSP (Scanning UV spectro-polarimeter) – slit spectro-polarimeter	300	24.72	3.09
EIP (EUV imaging polarimeter) – imaging polarimeter	550	45.32	5.66
ChroME (Chromospheric Magnetism Explorer) – imaging spectro-polarimeter	600	49.44	6.18
SUM	1900	156.56	19.57

Table 5-3: Housekeeping datarates of SolmeX.

Name	Kbit/s	Gbit/day	GB/day
AOCS-related (OS)	100	8.24	1.03
housekeepings (OS)	150	12.36	1.54
AOCS-related (CS)	100	8.24	1.03
housekeepings (CS)	150	12.36	1.54
SUM	500	41.20	5.15

5.3. Conclusions for the C&DG Throughput

In the following tables (Table 5-4, Table 5-5 and Table 5-6) one can find the overall throughput of data which has to be stored on the storage system and transferred to ground in one day. These numbers take the data filtering assumptions from Table 5-1 into account.

Table 5-4: Sum of data to be stored and transferred.

Data	Amount
Datarate of housekeepings and AOCS (5%)	0.26 GB/ day
Datarate of payload data (100%)	19.57 GB/ day
Size of the storage system regarding the required derivation time (24h)	19.83 GB
Required average datarate of the spacelink for payload data	1.90 Mbit/ s
Required average datarate of the spacelink for housekeeping and AOCS data	25.00 Kbit/ s

Table 5-5: Payload link scenario.

Data	Amount
Payload: Required datarate regarding the duration of contact per day (8h) (X-band)	5.7 Mbit/ s
Housekeepings/AOCS: Required datarate regarding the duration of contact per day (S-band)	75 Kbit/ s

Table 5-6: Intersatellite link scenario.

Data	Amount
Required datarate between OS and CS regarding the SUM of Housekeepings/AOCS data	1000 Kbit/ s

5.4. Baseline Design

5.4.1. Functional Partitioning on both Spacecraft

The block diagram shows the basic structure of the command and data handling systems on both satellites. They are based on the very same onboard-computer-system for easier software development and code reuse. Only a few peripheral blocks, which are not needed, are not

implemented on the Occulter S/C. Both systems are fully double-redundant for fault protection.

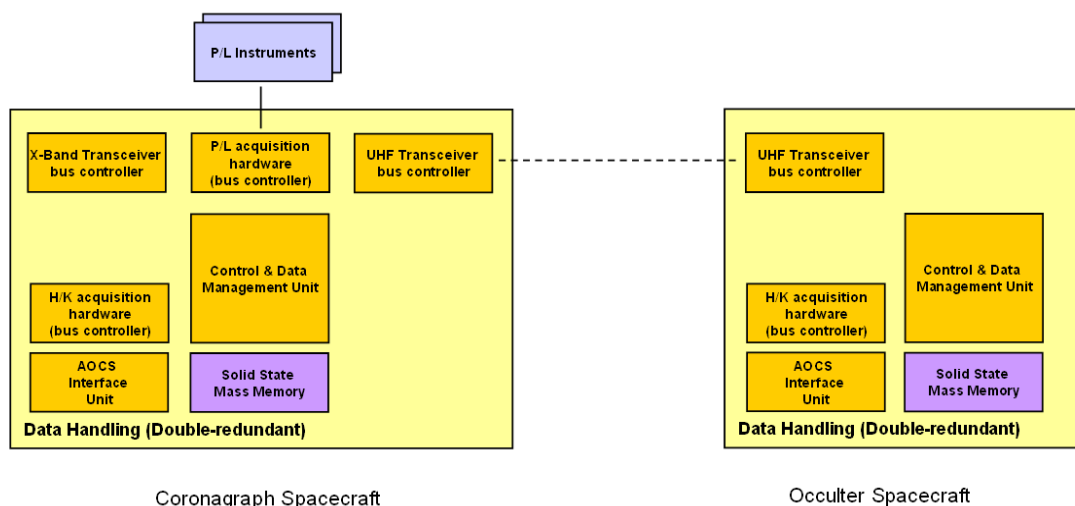


Figure 5-1: Functional partitioning on both spacecraft.

5.4.2. Hardware Specification Proposal

As hardware specification proposal a 32-Bit CPU with ARM-Core running at a speed of 40 MHz may fit. The Solid State Mass Memory Storage should have a capacity of 9 GB for 24 hours (incl. 10% margin). In the following tables you can see the power consumption estimates and the physical dimensions of the onboard computer boxes which are mounted on both S/C.

Table 5-7: Power consumption estimate of the DHS.

Property	Value
P_Peak	ca. 100 Watt
P_StandBy	ca. 20 Watt
Duty Cycle	70%

Table 5-8: Estimate of physical dimensions of the OBC box.

Property	Value
Height	300 mm
Width	185 mm
Depth	114 mm
Mass	12 kg incl. 10% Margin
Temperature range	ca. -30°C to 85°C
Radiation hardness	ca. 100 kRad to 200 kRad p.a.

The physical estimations are not based on specific hardware, but are an estimate of a suitable board size to hold all the necessary components like CPU, Solid State Mass Memory System and all the needed peripherals.

5.4.3. Software Architecture Proposal

The software architecture is based on a real time operating system like FreeRTOS (<http://www.freertos.org>) which is running on the OBCs hardware. The operating system has a powerful schedule mechanism to run several tasks in parallel. These tasks are explained in the following paragraphs.

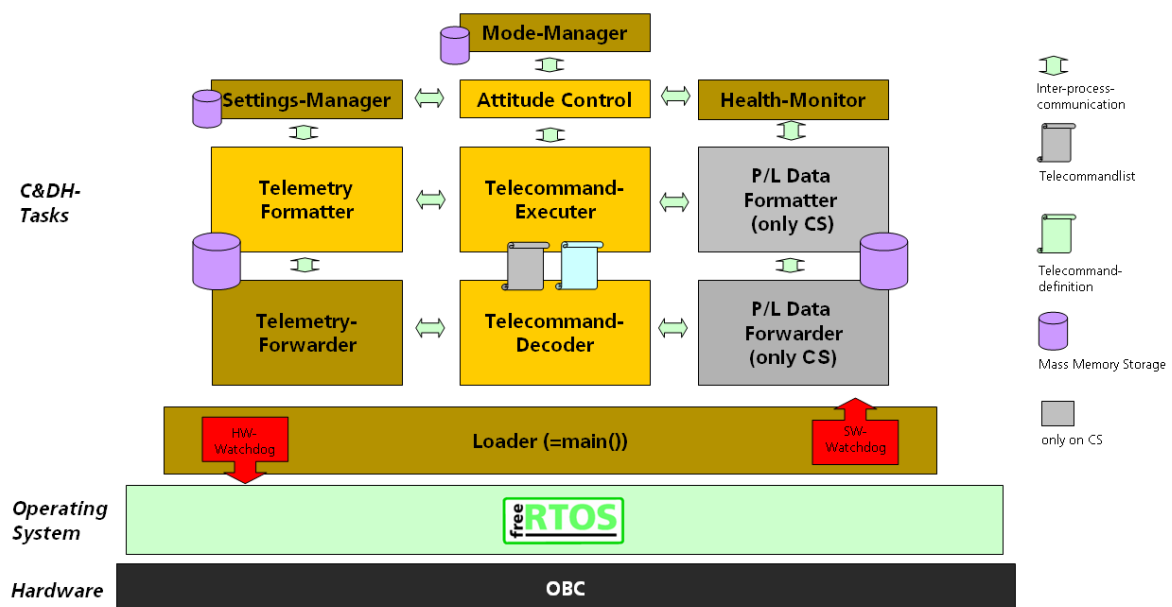


Figure 5-2: Software architecture block diagram.

Loader

Starts the other tasks and implements the hardware-watchdog timer reset as well as the software-watchdog. SW-Watchdog is a mechanism similar to the HW-Watchdog which periodically asks the tasks for their availability. If one task does not answer it will be killed and restarted by the loader. The other tasks will not be disturbed.

Telecommand-Decoder

Receives telecommands from the S-Band-Transceiver, validates them and stores them into the command list data structure. It uses the implementation of the telecommands. It runs as a parallel task on the real time operating system.

Telecommand-Executer

It is kind of scheduling mechanism which reads periodically from the command list if there are new commands to execute immediately or time-tagged. It uses the implementation of the telecommands too. It runs as a parallel task on the real time operating system.

Telemetry-Formatter

Gathers the housekeeping data from the several subsystems and stores them to a ringbuffer data structure on the storage system. It runs as a parallel task on the real time operating system.

Telemetry-Forwarder

Packages the housekeeping data and sends it through the S-Band-Transceiver to Ground. Does not run as a parallel task, it is invoked by the Telecommand-Executer if needed.

Payload Data Formatter

Gathers the payload data from the scientific instruments and stores them to a ringbuffer data structure on the storage system. It runs as a parallel task on the real time operating system. It is only implemented on the Coronagraph Spacecraft.

Payload-Forwarder

Packages the payload data and sends it through the X-Band-Transceiver to Ground. Does not run as a parallel task, it is invoked by the Telecommand-Executer if needed. It is only implemented on the Coronagraph Spacecraft.

Settings Manager

Reads and writes name-value pairs to the non-volatile memory on the storage system. So it implements a safe place where changed operational parameters can be stored. Does not run as a parallel task, it is invoked by any other task which needs access to the S/Cs settings.

Health-Monitor

Acts as a simple message- and error-log but could also be possible to monitor important values of the other tasks using inter-process-communication. It could also monitor other physical systems for their state of operation. In that case it would be a self-running task.

Mode-Manager

Does manage and provide the several spacecraft modes which are set by ground via receiving a telecommand or set autonomously. It does also provide the current operation mode to all other tasks.

Attitude Control

In the Attitude Control task methods are implemented which serve the AOCS system. Depending on the final design, this could be the whole closed loop control mechanism or just some methods which serve the AOCS indirectly.

5.4.4. List of Equipment Mass and Power Budget

The following two tables, Table 5-9 and Table 5-10, provide an overview over the mass and power budgets of the Data Handling System. As the system is identical for both spacecraft only Element 1 is presented here.

Table 5-9: Mass budget for the Data Handling system.

Element 1	SolmeX Coronagraph Spacecraft	MASS [kg]				
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	OBC	1	10,0	To be modified	10	11,0
2	Databus for H/K	1	0,5	To be modified	10	0,6
3	Databus for P/L	1	0,5	To be modified	10	0,6
SUBSYSTEM TOTAL		3	11,0		10,0	12,1

Table 5-10: Power budget for the Data Handling system.

Element 1	SolmeX Coronagraph Spacecraft		POWER SPECIFICATION PER MODE						PPEAK AND POWER SPECIFICATION PER MOD					
Unit	Unit Name	Quantity	Ppeak	ScM	ScM	ScM	FAM	FAM	FAM	SfM	SfM	SfM		
	Click on button above to insert new unit			Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby	Dc		
1	OBC	1	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	20,0	70,0		
2	Databus for H/K	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
3	Databus for P/L	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0		
SUBSYSTEM TOTAL		3	100,0	100,0	100,0		100,0	100,0		100,0	20,0			

5.4.5. Ground Station Data Handling

The table below shows a very rough estimation of the dimensions of the data archive on ground which is needed to store the scientific and operational data for a mission duration from 3 to 6 years.

Table 5-11: Data archive requirements on the ground.

	Capacity requirement	Database technology requirement
Scientific data archive (based on 3 to 6 years)	25 TB to 45 TB	Large BLOB capabilities
Operational/AOCS data archive (based on 3 to 6 years)	300 to 600 GB	mySQL, MS-SQL

5.5. Options and Trades

5.5.1. Fault Protection

The hardware fault protection could be realized by fully-redundant OBC-systems incl. storage as cold backup. Another stage would be to implement a hardware watchdog as part of the software architecture like explained above.

For ensuring the integrity of the software there should be a non-overridable software image in the rom at every time. Software updates could be done in addition to that but will not override the safe image. The second stage would be to implement the Software-Watchdog as part of the software architecture like shown above.

Also a command fault protection should be implemented. That could happen by introducing command-sequences for critical actions. That means no single command (which may have been corrupted during transmission) could cause a malfunction.

5.5.2. Software Development Tools

As a programming language it would be preferred ANSI C and partly Assembler. The ANSI C ensures usage of a widely-known programming language, which can also be easily serviced in the future. It is possible that instead embedded C++ will come into focus if the hardware platform has finally been selected.

5.6. Summary

The Onboard Computer should be identical on OS and CS. That ensures easy developing and code-reuse. Most of the operational software is identical on both systems, expect the payload tasks. The computer could be based on 32-Bit ARM architecture at 40 MHz. The operating system of choice would be FreeRTOS which has powerful scheduling mechanisms. The programming language would be ANSI C.

The expected sum of payload data is about 19.57 GB per day which has to be transferred to ground via X-Band. In addition there is 5.15 GB of housekeeping and AOCS data per day but only a percentage of 5% has to be transferred to ground via S-Band normally. The size of the storage system regarding the required derivation time of 24 h would be about 22 GB of solid state mass memory storage (incl. 10% margin).

The power consumption estimation is about 100 Watt (Peak) and 20 Watt (Standby) with 70% duty cycle. The physical size of the fully double redundant computer box could be about

300 x 185 x 114 mm over all. Mass is estimated at about 12 kg (incl. 10% margin). The system should operate in a temperature range from -30°C to +85°C and should have a radiation hardness of 100 to 200 kRad p.a.

The estimation for a scientific data archive is based on a mission duration from 3 to 6 years. For payload data a database of a size of 25 TB to 45 TB would be needed. The housekeeping and AOCS data could be archived in a database at a size of 300 GB to 600 GB.

6. Communication

6.1. Requirements and Design Drivers (or Assumptions)

The main requirements on system level which have impacts for the communication subsystem design are:

- Target Lifetime of 3 years
- Distance between the S/C > 100 m +/- 5 cm
- TRL 5 or higher for the design

Additional assumptions to be made are the distance between Earth and L_1 , which is set to an average value of 1.5 Mio km, and the biggest distance between points in the L_1 orbit. This has been decided to be an ellipse with a maximum semimajor-axis of 560,000 km (i.e. the diagonal worst-case for y- respectively z-amplitude of +/-400,000 km). Figure 6-1 shows the relations and the resulting angles which are as follows:

- $\alpha = 0.21^\circ$
- $\beta = 20.47^\circ$
- $\gamma = \alpha + \beta = 20.68^\circ$

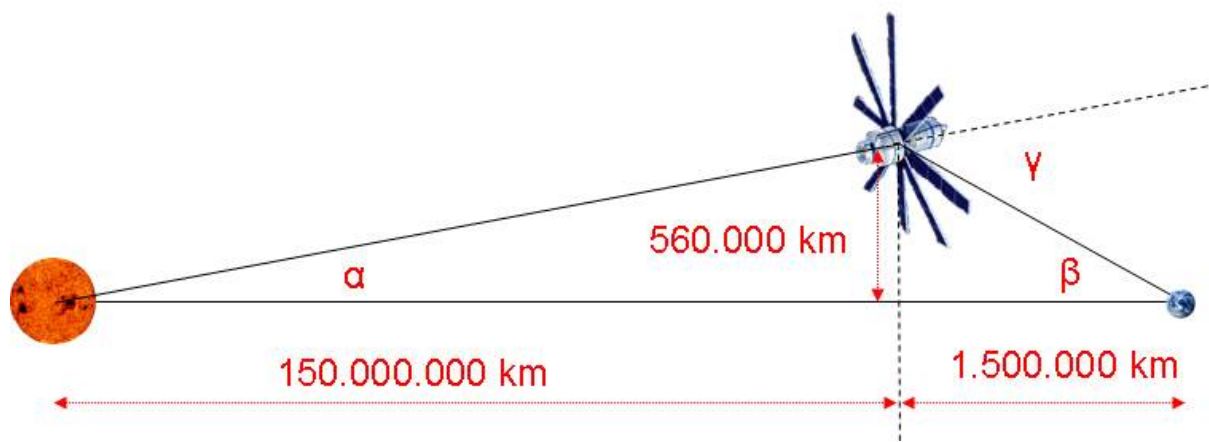


Figure 6-1: Distances between the spacecraft(s), Earth and the Sun.

The γ -angle is the most important angle for the link design since it represents the angular deviation from the combined space crafts line of sight to Earth. The respective communication angle, the half power beam width (HPBW) has to cover the γ -angle in both directions which results in a total angle of $2 * \gamma = 41.36^\circ$ for a potential fixed antenna system.

The daily communication window is estimated with 8 h/day and the continuously produced payload data rate is 2 Mbit per seconds (Mbit/s). This results in a transmission data rate of 6 Mbit/s taking the communication window into account.

6.2. Ground Station Contacts

According to the ESA ground station (G/S) network [RD 4], there are several opportunities for X-, S, and Ka-band systems using 15 m or 35 m deep space antennas for signal reception and transmission. In order to simplify the baseline design it has been assumed that there is contact with a suitable G/S for 1/3 of a day, as stated in 6.1. This assumption is a worst-case scenario since contact times are in the range of 8 to 10 hours (see Chapter 3.1.3). Table 6-1 shows the available G/S including their antenna gains for certain bands:

Table 6-1: ESA ground stations [RD 2].

Ground station	Size	Receive Band	Transmit band	G/T ratio ⁵
New Norcia	35 m	S & X (& Ka ⁶)	S & X	49.5 (& 54.9)
Cebreros	35 m	X & Ka	X & Ka ⁷	50.8 & 55.7
Kourou	15 m	S & X	S & X	29.9 & 41.4
Maspalomas	15 m	S & X	S	29.2 & 37.5
Perth	15 m	S & X	S & X	26.6 & 42.5
Malargue (under construction)	35 m	X & Ka	X & Ka ⁸	50.8 & 55.7

6.3. Options and Trades

There are several options for the design of the communication subsystem including frequency and component selection. Table 6-2 highlights the main decisions to be made between several options. The left column describes the issue whereas the middle and right column state different options. It could also be possible that none of these options is selected (e.g. no amplification instead of amplifier utilization).

Table 6-2: Different options for the communication design.

Orbit	GEO	L1 Earth-Sun
Antenna type	Parabolic Dish	Horn Antenna
Antenna mechanism	Fixed	Steerable
Amplifier Technology	Travelling Wave Tube (TWTA) e.g. 60 W RF Power	Solid State Power (SSPA) e.g. 12 W RF power
Frequency (Band) Payload	8450... 8500 MHz (X – Band)	25500 – 27000 (Ka – band)
Frequency (Band) From S/C to S/C	2200... 2290 MHz (S – Band)	300....800 Mhz (UHF)

On system level it has been decided to place the space crafts in the Earth-Sun-L₁ point instead of GEO due to the demand of continuous observation of the Sun. The other options are partially linked to each other and the trade results are described in the next chapter.

6.4. Baseline Design

The baseline design of the communication architecture incorporating the options and trades discussed above, leads to 7 different links which are shown in Figure 6-2:

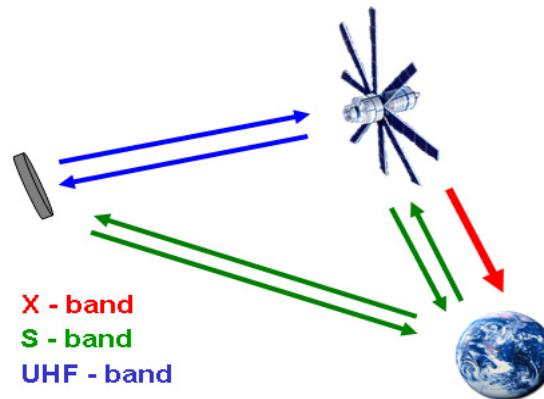


Figure 6-2: Communication links.

In order to reduce complexity of the overall system the instruments are exclusively accommodated on the Coronagraph S/C. This leads to only one downlink of the payload data. However, both S/C need to have Space-Earth communication for Telemetry, Tracking and Command (TT&C) which results in 4 links for housekeeping and command signals. Since both S/C are flying in formation the relative positioning has to be ensured which is supported by a bi-directional intersatellite link. The selection of frequencies and respective components for the two different space segments are as follows:

6.4.1. Payload data downlink (X-band)

The two main options for the payload data transmission are X- and Ka-band. According to the ITU regulations the bandwidth of X-band communication is limited to 50 MHz (between 8450 and 8500 MHz). This is the total bandwidth which has to be shared by all agencies. The data rate of 6 MHz (considering already the 33% duty cycle) will increase depending on the applied coding scheme. This is necessary for signal safety and an additional gain due to the reduced energy bit to noise ratio (E_b/N_0) in the link budget. On the other hand, coding consumes additional bandwidth. Ka-band provides up to 1500 MHz bandwidth within the carrier frequency range of 25.5 - 27 GHz or 500 MHz within the Deep Space (DS) frequency range of 31.8 - 32.3 GHz. Unfortunately the available ESA Ground Stations are not designed for the lower range and according to the ECSS-E-ST-50-05C standard [RD 4] the higher range is reserved for deep space missions which apparently requires more than 2 Mio km distance to the Earth. The antenna gain, which increases by using Ka-band instead of X-band will be compensated by the higher free space losses which both include the wavelength in their calculations. The higher Ka-band gain on the G/S side will be even overcompensated by the additional rain losses which are due to the lower wavelengths. An additional advantage is that X-band allows the common utilization of S- and X-band with one 35m G/S antenna, i.e.

New Norcia which would currently not the case for Ka-band. These trades result in the decision for X-band as preferred and baseline P/L communication link.

The payload data downlink has to be performed with a steerable antenna in order to cope with the deviants of the S/C-Sun line of sight compared to the Earth-Sun ecliptic of up to 41.36° (see also 6.1). A fixed antenna with such a HPBW would require significantly more power to compensate the reduced antenna gain. The antenna will be a parabolic dish instead of a horn design to further increase the gain. Furthermore, a travelling wave tube amplifier (TWTA) is foreseen instead of an solid state power amplifier (SSPA) since the radio frequency power is relatively high and the TWTA – which requires a minimum mass increasing set of additional components - has a higher efficiency and hence reduces the overall power consumption.

6.4.2. TT&C up-/downlinks (S-band)

For the housekeeping data transmission and command signal reception a conventional S-band communication is foreseen. Both S/C are carrying the same equipment which follows a 100% redundant approach providing omni-directional coverage using patch antennas. This antenna type is very robust, simple and provides data rates of up to 10 kbps (see also section 6.5). The receiving equipment is switched on all the time besides the launch phase in order not to interfere with the electrical equipment of the launch vehicle. It allows signal reception during safe mode and any other tumbling manoeuvres. The frequency range is between 2200 and 2290 MHz which is more than sufficient for the current possible data rate.

6.4.3. Intersatellite communication (UHF-band)

In order to avoid interference with the S/C to Earth communication, especially during formation acquisition and within tumbling phases (e.g. safe mode), the intersatellite communication will be performed in UHF. The distance between the S/C of about 100 m still allows a very high amount of data to be shared between them for formation flying.

6.5. Link Budget

Within this chapter the link budgets for the critical P/L and TT&C communication are presented. The design has been concentrated on the downlink path for each band since these links have higher limitations due to the power consuming data transmission on the S/C side. For the different link budgets, the technical assumptions and decisions can be found within the yellow marked fields within Figure 7-1. The green marked fields are computed using these inputs. The link margin has to be higher than 3 dB. Please note that this figure does not provide every contribution to the link budget. Further information can be found in the SolmeX data model, i.e. the IDM [RD 5].

X - BAND DOWNLINK				
		Unit	Linear	Dezibel
Data Rate				
Input Data rate	R_b	kbit/s	2000,00	
Input Data rate	R_b	Mbit/s	2,00	63,01
Bandwidth		Mhz	15,00	71,76
BER			1,00E-09	
Coding type			Red Salomon (255,223)	
Req. EN/No with coding				7,00
Comms Duty Cycle		%	33,00%	
Data rate Output	R_c	M/bits	6,93	68,41
Antenna Gain				
Frequency [GHz]			8,45	
wavelength [m]			0,036	
Transmitter Power		W	60,00	17,78
Transmitter Antenna Type			Parabolic Dish	
Transmitter diameter [m]		m	0,30	
Half Power Beam Width		°	8,28	
EIRP				40,67
Receiver diameter [m]	A_D		35,00	New Norcia
	G/T	dB/K		49,50
Path loss				
Path length		m	1,50E+09	
Path loss; Free Space loss			2,82E+23	234,50
Propag. & Polarization loss				0,50
Atmospheric loss				0,50
Rain loss				3,00
				240,29
Overall				
1/Boltzman Constant		dBW/HzK		228,60
Achieved C/No				78,47
Achieved Eb/No				10,07
Link margin				3,07

S - BAND DOWNLINK				
		Unit	Linear	Dezibel
Data Rate				
Input Data rate	R_b	kbit/s	10,00	
Input Data rate	R_b	Mbit/s	0,01	40,00
Bandwidth		Mhz	10,00	70,00
BER			1,00E-06	
Coding type			Red Salomon (255,223)	
Req. EN/No with coding				6,50
Comms Duty Cycle		%	33,00%	
Data rate Output	R_c	M/bits	0,0303	44,81
Antenna Gain				
Frequency [GHz]			2,20	
wavelength [m]			0,136	
Transmitter Power		W	10,00	10,00
Transmitter Antenna Type			Patch Antenna	
Transmitter diameter [m]		m	0,07	
EIRP				11,00
Receiver diameter [m]	A_D		35,00	New Norcia
	G/T	dB/K		40,00
Path loss (simple)				
Path length		m	1,50E+09	
Path loss; Free Space loss			1,91E+22	222,81
Propag. & Polarization loss				0,10
Atmospheric loss				0,10
Rain loss				0,00
				224,80
Overall				
1/Boltzman Constant		dBW/HzK		228,60
Achieved C/No				54,80
Achieved Eb/No				9,98
Link margin				3,48

Figure 6-3: X-band and S-band link budgets (downlink).

6.6. List of Equipment Mass and Power Budget

This section includes the list of components which are linked to their respective quantity, mass, maturity level and power consumption per mode. The modes are explained in Chapter 2.4.1.

6.6.1. Mass Budgets

Table 6-3 and Table 6-4 show the equipment lists and mass budgets of the communication subsystem of SolmeX' two spacecraft.

Table 6-3: Mass budget for the communication subsystem of the Coronagraph S/C.

Element 1	SolmeX Coronagraph Spacecraft	MASS [kg]				
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	S-band antenna (low-gain; patch)	2,00	0,40	To be modified	10	0,9
2	S-band transceiver; coherent (ComTech)	1,00	0,70	To be modified	10	0,8
3	S-band transceiver (cold-red.)	1,00	0,70	To be modified	10	0,8
4	S-band transfer switch	1,00	0,20	To be modified	10	0,2
5	S-band Filters etc	2,00	1,00	To be modified	10	2,2
6	UHF antenna (omnidirectional)	2,00	0,20	To be modified	10	0,4
7	UHF transceiver	2,00	1,00	To be modified	10	2,2
8	UHF switch; filter	2,00	1,00	To be modified	10	2,2
9	X - band antenna	1,00	2,00	To be modified	10	2,2
10	X - band antenna mechanism (SSTL)	1,00	2,00	To be modified	10	2,2
11	X - band amplifier TWTA (60W output)	2,00	1,50	To be modified	10	3,3
12	X - Band modulator	2,00	1,00	To be modified	10	2,2
13	X - band Isolator	2,00	0,50	To be modified	10	1,1
-			0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		13	18,8		10,0	20,7

Table 6-4: Mass budget for the communication subsystem of the Occulter S/C.

Element 2	SolmeX Occulter Spacecraft	MASS [kg]				
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	S-band antenna (low-gain; patch)	2,00	0,40	To be modified	10	0,9
2	S-band transceiver; coherent (ComTech)	1,00	0,70	To be modified	10	0,8
3	S-band transceiver (cold-red.)	1,00	0,70	To be modified	10	0,8
4	S-band transfer switch	1,00	0,20	To be modified	10	0,2
5	S-band Filters etc	2,00	1,00	To be modified	10	2,2
6	UHF-antenna (omnidirectional)	2,00	0,20	To be modified	10	0,4
7	UHF transceiver	2,00	1,00	To be modified	10	2,2
8	UHF switch; filter	2,00	1,00	To be modified	10	2,2
-			0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		8	8,8		10,0	9,7

6.6.2. Power Budgets

For the power budget, only the science mode, the formation acquisition mode and the safe mode are displayed. During these phases the S-band transceivers are switched on continuously in order to be prepared receiving signals from the G/S. The duty cycle for the payload data transmission is estimated as 40 % (instead of 33%) in order to cover the phases when the equipment is turned on and off. The budgets are summarized in Table 6-5 and Table 6-6.

Table 6-5: Power budget for the communication subsystem of the Coronagraph S/C.

Element 1	SolmeX Coronagraph Spacecraft											
Unit	Unit Name	Quantity	ScM Pon	ScM Pstby	ScM Dc	FAM Pon	FAM Pstby	FAM Dc	StM Pon	StM Pstby	StM Dc	
	Click on button above to insert new unit											
1	S-band antenna (low-gain; patch)	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
2	S-band transceiver; coherent (ComTech)	1,00	10,0	0,0	100,0	10,0	0,0	10,0	10,0	0,0	100,0	
3	S-band transceiver (cold-red.)	1,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
4	S-band transfer switch	1,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
5	S-band Filters etc	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
6	UHF antenna (omnidirectional)	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
7	UHF transceiver	2,00	10,0	0,0	100,0	10,0	0,0	100,0	10,0	0,0	0,0	
8	UHF switch; filter	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
9	X - band antenna	1,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
10	X - band antenna mechanism (SSTL)	1,00	5,0	0,0	100,0	5,0	0,0	100,0	5,0	0,0	100,0	
11	X - band amplifier TWTA (60W output)	2,00	150,0	0,0	40,0	150,0	0,0	0,0	150,0	0,0	0,0	
12	X - Band modulator	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
13	X - band Isolator	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	

Table 6-6: Power budget for the communication subsystem of the Occulter S/C.

Element 2	SolmeX Occulter Spacecraft											
Unit	Unit Name	Quantity	ScM Pon	ScM Pstby	ScM Dc	FAM Pon	FAM Pstby	FAM Dc	StM Pon	StM Pstby	StM Dc	
	Click on button above to insert new unit											
1	S-band antenna (low-gain; patch)	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
2	S-band transceiver; coherent (ComTech)	1,00	10,0	0,0	100,0	10,0	0,0	100,0	10,0	0,0	100,0	
3	S-band transceiver (cold-red.)	1,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
4	S-band transfer switch	1,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
5	S-band Filters etc	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
6	UHF-antenna (omnidirectional)	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
7	UHF transceiver	2,00	10,0	0,0	100,0	10,0	0,0	100,0	10,0	0,0	100,0	
8	UHF switch; filter	2,00	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	
-												
	SUBSYSTEM TOTAL	8	30,0	0,0		30,0	0,0		30,0	0,0		

6.7. To be studied / additional Consideration

In this section some major and minor options for improvements of backup scenarios are describes as well as issues which still have to be iterated for the current design.

6.7.1. Optional Ka-band P/L data downlink

The availability of ~26 GHz Ka-band ground stations in Europe for deep space missions with less than 2 Mio km distance to Earth as well as the utilization of the NASA Deep Space Network (DSN), which has been used for SOHO, has not been investigated in detail. The final

decision of the frequency band selected for the payload communication downlink is not fixed and could be switched to Ka-band if there are limitations with respect to the X-band bandwidth. In principle, both designs would be similar using the same arrangement of components with possible other options and maturity levels.

6.7.2. Housekeeping data transmission increase

The current design, using a S-band patch antenna, does not allow higher data rates (continuously produced and transmitted within 8 out of 24 hours) than 10 kbps. A parabolic dish, which has a much higher antenna gain allows bit rates of up to 100 kbps with a similar antenna as for the X-band system (i.e. 0.3m in diameter) and covers about 80% of the required HPBW. Higher data rates require even larger antenna diameters which lead to lower HPBW and hence additional steering mechanisms and space for accommodation purposes have to be foreseen.

6.7.3. Further options

In order to improve the links and ensure high(er) data rates the following aspects should be investigated in more detail:

- L₁ orbit (lower orbit reduces the 41.36° angle and provides more flexibility)
- Coding schemes (coding gain could be increased but this consumes bandwidth)
- X-band antenna size (larger diameter increases link margin but needs more space)

Additionally still a horn antenna could be used for X-band transmission but this reduces the data rate and/or increases the power consumption. It could be installed as a back-up taking the same RF power equipment as identified for the parabolic dish antenna. This would slightly contribute to the mass budget but offers a second – downgraded – data transmission opportunity.

6.7.4. Open issues

Aspects which have not been investigated in detail during the study but contribute to the baseline design and alignments with other subsystems are:

- UHF link budget
- Availability of NASA Deep Space Network
- Exact frequency allocation of each band
- Housekeeping data refinement
- Antennas accommodation
- Design and control of the x-band antenna mechanism

6.8. Summary

The SolmeX Communication Subsystem is divided into three parts, each representing an independant communication link with its own frequency:

- an X-band downlink (at 8.45 GHz) from the Coronagraph S/C to Earth,
- S-band up- and downlink (at 2.2 GHz) from each S/C to Earth and vice versa,
- UHF communication between the S/Cs in both directions.

The X-band communication is able to transmit the continuously produced 2 Mbit/s payload (P/L) data within one Earth day using a duty cycle of 33% (8/24 hours). Including coding this leads to a total data rate of ~7 Mbit/s during the communication phase. A steerable 0.3 m antenna compensates the angular deviation from the Earth-Sun line of sight (20.68° in each direction) and ensures a downlink whenever possible. Two redundant travelling wave tube amplifiers (TWTA) with 60 W output power and the utilization of a 35 m antenna in New Norcia ensures a sufficient link margin for the P/L communication. A traditional and redundant S-band system with omni-directional coverage leads to a potential full time-tracking of the S/C, if required. UHF equipment is used for ~100 m intersatellite communication in order to avoid frequency interference with the Space-Earth communication. The S- and UHF-band equipment is equal on both S/C and X-band is only used on the Coronagraph element. The equipment is state of the art and higher than TRL 5. The mass values, including 10% component margins, are 20.7 kg for the Coronagraph- and 9.7 kg for the Occulter-S/C.

7. Power

7.1. Requirements and Design Drivers

The requirements and assumptions for the power subsystem design are listed below:

- Mission Life Time 3 Years (T) 6 Years (G)
- Components of power subsystem shall have TRL > 5
- Battery design for Safe Mode (see Figure 7-1)
- All other phases will be supplied by a solar generator (S/G)
- After Fregat separation Coronagraph S/C and Occulter S/C use their own S/G

7.2. Modes of Operation

The design of the power subsystem has to meet the requirements of all operation modes to ensure the success of the mission. Therefore the whole mission was divided into power operation modes (different from the system defined modes) which are relevant to the power subsystem design. As shown in the Figure 7-1 all modes except Separation Mode and Safe Mode are supplied either by the launcher or by a solar generator of the spacecraft. For the Separation Mode the time period from separation from launcher to the deployment of the solar array is assumed to be approximately 10 min. Safe Mode is more critical regarding battery power consumption. Within this mode both satellites have to be supplied by a secondary power source because in the worst case there is no power available from S/G at all. To recover the system, it is assumed to supply the emergency components for 30 h by battery power.

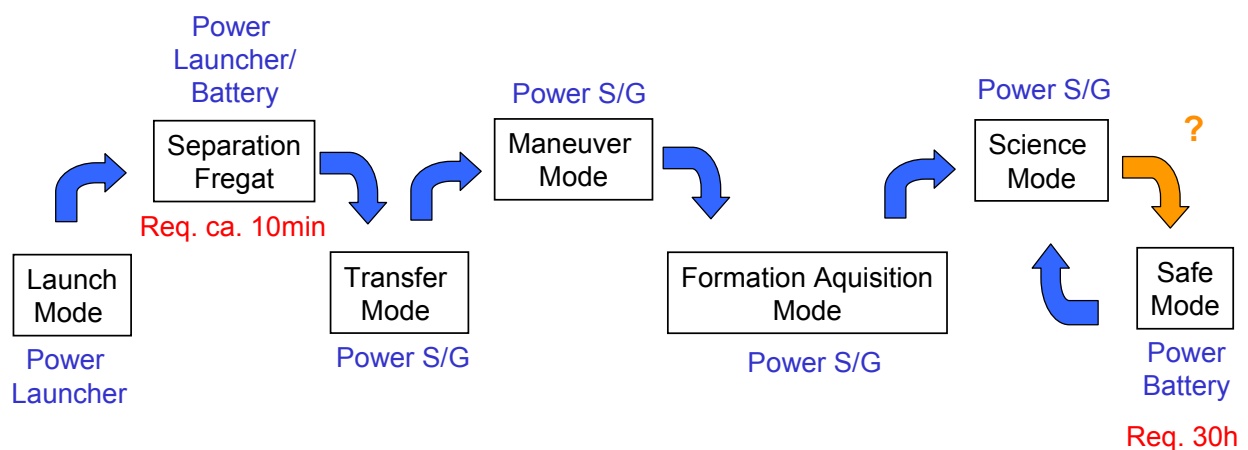


Figure 7-1: Modes of operation as used for the layout of the power system.

7.3. Baseline Design

The baseline power subsystem design is shown in Figure 7-2. The Solar Array generates electrical power, which has to be conditioned to 28 V by the PCU. The PCU also include the battery charge and discharge regulator (BCR / BDR) which allow to charge the battery and to take out the power during peak power demand or during Safe Mode and Separation Mode as shown in Figure 7-1.

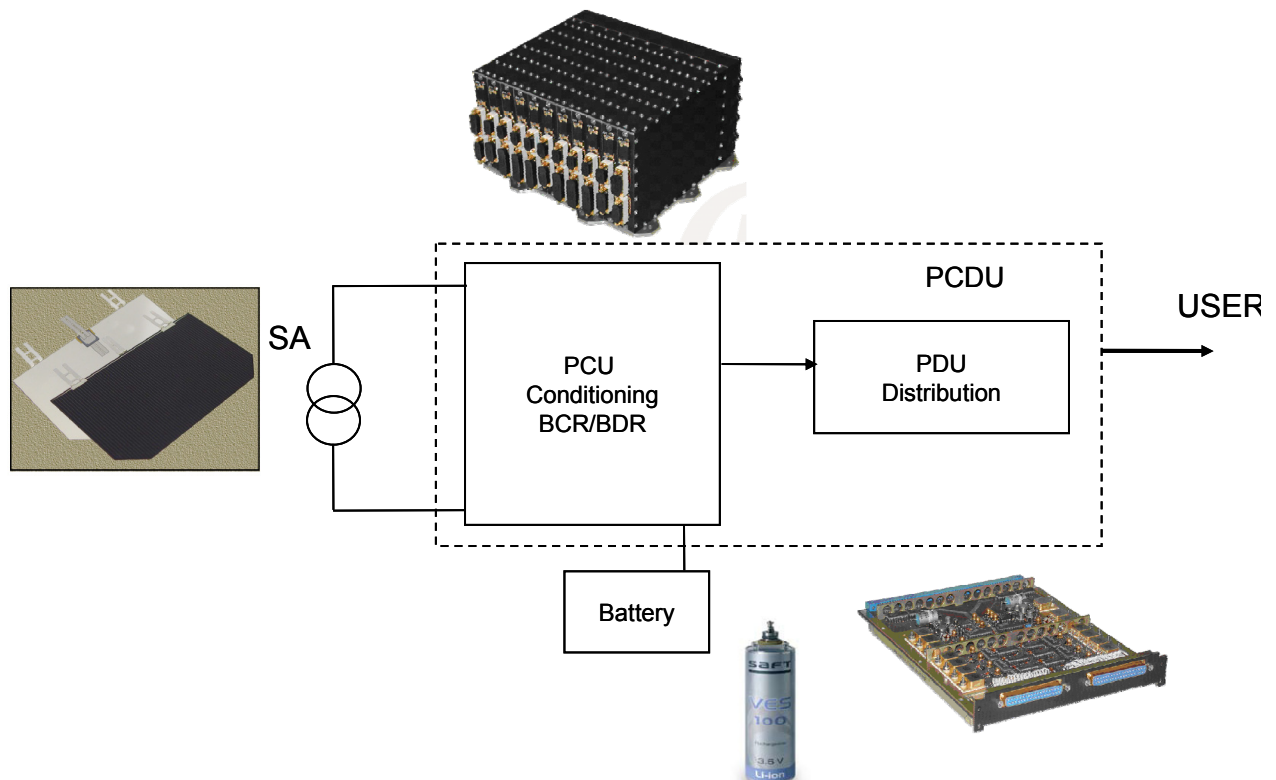


Figure 7-2: Baseline design of the Power subsystem.

The components used for the power subsystem are listed below:

Solar cells:

- Spectrolab
- UTJ GaAs cells, 28.3%
- Missions: more than 675kW in Orbit

SAFT Batteries:

- 72 Coronagraph S/C
- 48 Occulter S/C
- Missions: e.g. Calipso, Corot

Terma PCU /PDU:

- Power Conditioning Unit
- Missions: e.g MarsExpress, Venus Express

- Power Distribution Unit
- Missions: e.g. XMM-Newton, Integral

7.3.1. Primary Power Design (S/G)

The S/G design for Coronagraph S/C and Occulter S/C is based on the power demand of all subsystems (incl. power itself) and the instruments during all modes (see Table 7-1 and Table 7-2). The design of S/G has been performed for peak power demand. This means $P_{d, \text{coronagraph}} = 800 \text{ W}$ and $P_{d, \text{occulter}} = 370 \text{ W}$. Furthermore the degradation has been assumed as 3.75 % p.a. (worst case) and the solar constant at Lagrange Point $L_1 = 1395 \text{ W/m}^2$.

Table 7-1: Power requirements w.r.t. the Coronagraph S/C.

Req. el. Power P_{sa}	941 W
el. power day (sun) P_d	800,00 W
el. power eclipse P_e	0,00 W
efficiency day (sun) X_d	0,85
efficiency eclipse X_e	0,65
time of Illumination T_d	1,00 s
time of eclipse T_e	0,00 s
el. Power $P_0 = \epsilon \cdot I_s$ (Energy gain)	279 W/m²
efficiency solar cells ϵ	20,00 %
el. Power PBOL	215 W/m²
Inh. degradation I_d	0,77
sun angle	0,00 °
el. Power PBEL	170,78 W/m²
degradation L_d (life time)	0,80 %
Req. Solar Area A_{sa}	5,51 m²
Selected Area (selected)	5,50 m²
Area per solar cell	0,0032 m ²
Solar cell quantity (calculated)	1722 Qty
Solar cell quantity (selected)	1719 Qty
Mass per cell	0,84 kg/m ²
Mass for e.g. adhesives, polyimide film	0,12 kg/m ²
Mass (cells w/o margin)	5,3 kg

Table 7-2: Power requirements w.r.t. the Occulter S/C.

Req. el. Power P_{sa}	435 W
el. power day (sun) P _d	370,00 W
el. power eclipse P _e	0,00 W
efficiency day (sun) X _d	0,85
efficiency eclipse X _e	0,65
time of Illumination T _d	1,00 s
time of eclipse T _e	0,00 s
el. Power P₀=ε*I_s (Energy gain)	279 W/m²
efficiency solar cells ε	20,00 %
el. Power P_{BOL}	215 W/m²
Inh. degradation I _d	0,77
Sun angle	0,00 °
el. Power P_{BEL}	170,78 W/m²
degradation L _d (life time)	0,80 %
Req. Solar Area A_{sa}	2,55 m²
Selected Area (selected)	2,60 m²
Area per solar cell	0,0032 m ²
Solar cell quantity (calculated)	797 Qty
Solar cell quantity (selected)	813 Qty
Mass per cell	0,84 kg/m ²
Mass for e.g. adhesives, polyimide film	0,12 kg/m ²
Mass (cells w/o margin)	2,5 kg

7.3.2. Secondary Power Design (Batteries)

The secondary power design is also based on power budget shown in Table 7-1 and Table 7-2.

- Coronagraph S/C → 180W
- Occulter S/C → 120W

Table 7-3: Battery layout of the Coronagraph S/C.

Battery string	8,00 Qty
Strings quantity	9,00 Qty
Battery quantity	72,00 Qty
req. power in SfM	180,00 W
DoD	80 %
Capacity per battery cell C _{av_1}	95,60 Wh
Capacity C _{av_80%}	5507 Wh
Operation Time (only Battery)	30,6 h
Mass (battery w/o margin)	58,3 kg

Table 7-4: Battery layout of the Occulter S/C.

Battery string	8,00 Qty
Strings quantity	6,00 Qty
Battery quantity	48,00 Qty
req. power in SfM	120,00 W
DoD	80 %
Capacity per battery cell C_av_1	95,60 Wh
Capacity C_av_80%	3671 Wh
Operation Time (only Battery)	30,6 h
Mass (battery w/o margin)	38,9 kg

7.3.3. List of Equipment and Mass Budget

The mass budget is based on following assumptions:

- Cells:
0.84 kg/m² (0,036m²→ ca. 0,003kg/cell)
- Adhesives, polyimide film:
0.12 kg/m²
- Coverglass+Honeycomb: in structure budget (100µm)
- PCU / PDU
(8,3kg / ,55kg each)

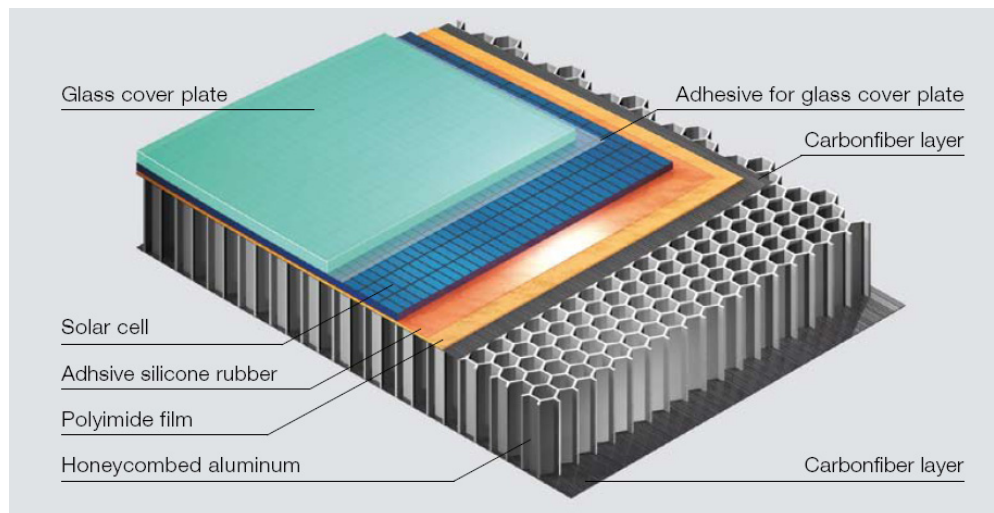


Figure 7-3: Baseline design of the Power subsystem.

Table 7-5, Table 7-6, Table 7-7 and Table 7-8 show the mass budget of Coronagraph and Occulter S/C and also the equipment list of the power subsystem.

Table 7-5: Mass budget of power subsystem of the Coronagraph S/C.

Element 1	SolmeX Coronagraph Spacecraft		MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	Solar Array (TJ-GaAs 20% BOL)	3	1,8	To be modified	10	5,8
2	Battery	72	0,8	To be modified	10	64,2
3	PCU	1	8,3	To be modified	10	9,1
4	PCU	1	8,3	To be modified	10	9,1
5	PDU	1	0,6	To be modified	10	0,6
6	PDU	1	0,6	To be modified	10	0,6
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		6	81,3		10,0	89,4

Table 7-6: Mass budget of power subsystem of the Occulter S/C.

Element 2	SolmeX Occulter Spacecraft		MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	Solar Array (TJ-GaAs 20% BOL)	1	2,4	To be modified	10	2,6
2	Battery	48	0,8	To be modified	10	42,8
3	PCU	1	8,3	To be modified	10	9,1
4	PCU	1	8,3	To be modified	10	9,1
5	PDU	1	0,6	To be modified	10	0,6
6	PDU	1	0,6	To be modified	10	0,6
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		6	59,0		10,0	64,9

Table 7-7: Equipment list of power subsystem of the Coronagraph S/C.

Element 1	SolmeX Coronagraph Spacecraft		DIMENSIONS [m]		
Unit	Unit Name	Quantity	Dim1 Length	Dim2 Width or D	Dim3 Height
	Click on button above to insert new unit				
1	Solar Array (TJ-GaAs 20% BOL)	3	1,50	1,00	0,00
2	Battery	72	0,05	0,19	0,00
3	PCU	1	0,25	0,16	0,08
4	PCU	1	0,25	0,16	0,08
5	PDU	1	0,25	0,20	0,03
6	PDU	1	0,25	0,20	0,03
-	Click on button below to insert new unit				-
SUBSYSTEM TOTAL		6			

Table 7-8: Equipment list of power subsystem of the Occulter S/C.

Element 2	SolmeX Occulter Spacecraft		DIMENSIONS [m]		
Unit	Unit Name	Quantity	Dim1 Length	Dim2 Width or D	Dim3 Height
	Click on button above to insert new unit				
1	Solar Array (TJ-GaAs 20% BOL)	1	1,50	1,00	0,00
2	Battery	48	0,05	0,19	0,00
3	PCU	1	0,25	0,16	0,08
4	PCU	1	0,25	0,16	0,08
5	PDU	1	0,25	0,20	0,03
6	PDU	1	0,25	0,20	0,03
-	Click on button below to insert new unit				-
SUBSYSTEM TOTAL		6			

7.3.4. Power Budget

The following tables give an overview of power demand for each mode and the peak power for Coronagraph S/C and Occulter S/C.

Table 7-9: Power budget of the Coronagraph S/C.

ELEMENT 1			Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
			LM	TM	MM	ScM	FAM	SfM	0,0	-	-	-
Unit name	Quantity	Ppeak (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)
Power			0,3	11,7	11,7	1,0	11,7	13,2	0,3	0,0	0,0	0,0
Thermal			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
AOCS			0,0	0,0	163,6	111,8	126,8	77,2	17,0	0,0	0,0	0,0
Communication			0,0	10,0	30,0	30,0	21,0	10,0	143,0	0,0	0,0	0,0
Propulsion			28,0	4,0	35,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Data Handling			100,0	100,0	100,0	100,0	100,0	76,0	100,0	100,0	100,0	100,0
Life Support			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Mechanisms			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
GNC			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Descent & Landing			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Pyrotechnics			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Instruments			0,0	4,0	41,0	196,0	0,0	0,0	0,0	0,0	0,0	0,0
System power consumption (W)		795,5	128,3	129,7	381,3	438,8	259,5	176,4	260,3	100,0	100,0	100,0
System energy consumption (Wh)			4618,8	305148,5	190,7	5046,2	1038,2	5290,8	0,0	#WERT!	#WERT!	#WERT!

Table 7-10: Power budget of the Occulter S/C.

ELEMENT 2			Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
			LM	TM	MM	ScM	FAM	SfM	-	-	-	-
Unit name	Quantity	Ppeak (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)	Pav (W)
Power			0,6	12,5	12,5	2,0	12,5	14,0	0,6	0,0	0,0	0,0
Thermal			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
AOCS			0,0	0,0	103,0	44,3	59,3	0,0	9,6	0,0	0,0	0,0
Communication			0,0	10,0	21,0	30,0	30,0	30,0	143,0	0,0	0,0	0,0
Propulsion			12,0	36,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Data Handling			100,0	100,0	100,0	100,0	100,0	76,0	100,0	100,0	100,0	100,0
Life Support			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Mechanisms			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
GNC			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Descent & Landing			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Pyrotechnics			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Instruments			0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
System power consumption (W)		369,0	112,6	158,5	236,5	176,3	201,8	120,0	253,2	100,0	100,0	100,0
System energy consumption (Wh)			4053,6	372862,6	118,3	2027,5	807,3	3600,6	#WERT!	#WERT!	#WERT!	#WERT!

7.4. To be studied / additional Consideration

In addition to the performed analysis of the power subsystem, the following aspects are to be investigated in more detail:

- Thermal analysis for each mode for:
 - Solar Cells
 - Batteries
- Power consumption of all subsystems and payload
- Power losses for the converters

7.5. Summary

During the CE-Study the power subsystem was designed to meet the previous defined requirements. This includes the definition of Modes of Operation and identification of the worst case scenario for design of primary and secondary power supply. The secondary power supply is designed for Safe Mode during which the batteries have to provide enough energy for emergency components for 30 h to allow spacecraft recovery when necessary.

For the primary power supply it is assumed that the Coronagraph S/C and Occulter S/C operate on their own S/Gs. The design has been made to meet the peak power values for each S/C, i.e. ca. 800 W for the Coronagraph and 370 W for the Occulter. The selected components of the power subsystem have TRL > 5 as required. The total mass of the power subsystem for the Coronagraph S/C amounts to 89.4 kg and for the Occulter S/C to 64.9 kg incl. a margin of 10% of subsystem level.

8. Thermal

8.1. Requirements and Design Drivers (Assumptions)

The Thermal Control System (TCS) of the Coronagraph S/C and also of the Occulter S/C have to ensure that the required working temperature ranges for all instruments, components and subsystems of the satellite are not exceeded in any mission phase. The SolmeX TCS will be mostly passive and uses merely the dissipated heat of all components of the system S/C and Payload, except the special requirements of sensor cooling and batteries.

During the course of the study the system requirement regarding instrument temperature has been modified to be between 17 and 23°C, with a stability of 0.1 K for 10 min for each of the optical benches.

Each Sensor Near Electronic (SNE) will have app. 2 to 3 W. The rest of the power of the instruments will be located into the instruments E-boxes outside of the optical bench.

For the S/C components and the instruments E-boxes a temperature range from -20° C to +60° C will be defined. Special requirements for components are not defined up to now.

The solar limb viewing instruments outside the optical window must be protected against solar radiation. The same is true for the Occulter S/C.

8.2. Options and Trades

As result of the study a structural baseline design was fixed, which can be seen in Figure 8-1.

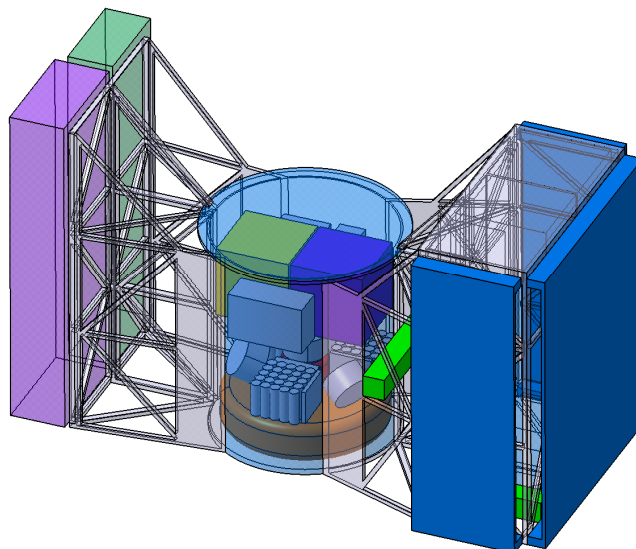


Figure 8-1: S/C baseline design.

For the thermal subsystem the TCS components and their positioning were discussed. Because of the different temperature ranges for the instrument parts and electronic components it is required to build several TCS subsystems.

- TCS for the focal plane and the SNE (separate for each instrument)
- TCS for the optical benches (separate for each instrument)
- TCS for the Coronagraph S/C including the instruments e-boxes
- TCS for the Occulter S/C

For each sub-TCS the positioning of the components was discussed. A final definition must be studied. For these, the actual values for power loads of the instruments as well as for the S/C components and the external heat load, q_{ext} , must be studied.

8.3. Baseline Design

To protect the instruments outside of the maneuvering mode, a dust cover is required for each instrument optical window. A front shield with a second surface mirror (SSM) will be used to protect the solar disk viewing instruments as well as the Occulter S/C around the solar cell area.

Each instrument will get at least one emergency heater, which has to work during LM, TM, MM and SfM. The external heat loads (q_{ext}) are uniform (outside LM, TM and MM) - 0 W/m² for solar limb viewing instruments or 1400 W/m² for solar disk viewing instruments. MLI will be used to protect each instrument and the overall Coronagraph S/C and Occulter S/C. Emergency heaters for the S/C batteries will be used for the Coronagraph S/C and also the Occulter S/C. The Occulter solar disk viewing side will be protected by a SSM surface around the solar cells. A part of the Occulter cylinder or the back side of the Occulter plate will be used for radiation.

The TCS for the Coronagraph S/C including the instruments' e-boxes as well as the TCS for the focal plane and the SNE and for the optical benches is shown for one instrument in principal in the following drawing.

For each instrument two or more independent TCS have to be placed (one for the sensor, one or more for the optical parts at the bench), which can be seen in Figure 8-2. Each of these TCS will have as minimum one heater, one radiator, one heat transfer line and one or more temperature sensors. Each instrument will have an own MLI. The bench is mounted thermally insulated on the S/C.

For the S/C TCS one or more radiators will be used. For each e-box and S/C component one or more temperature sensor will be used in case these units are not equipped with own sensors. For each unit a temperature reference point (TRP) must be defined.

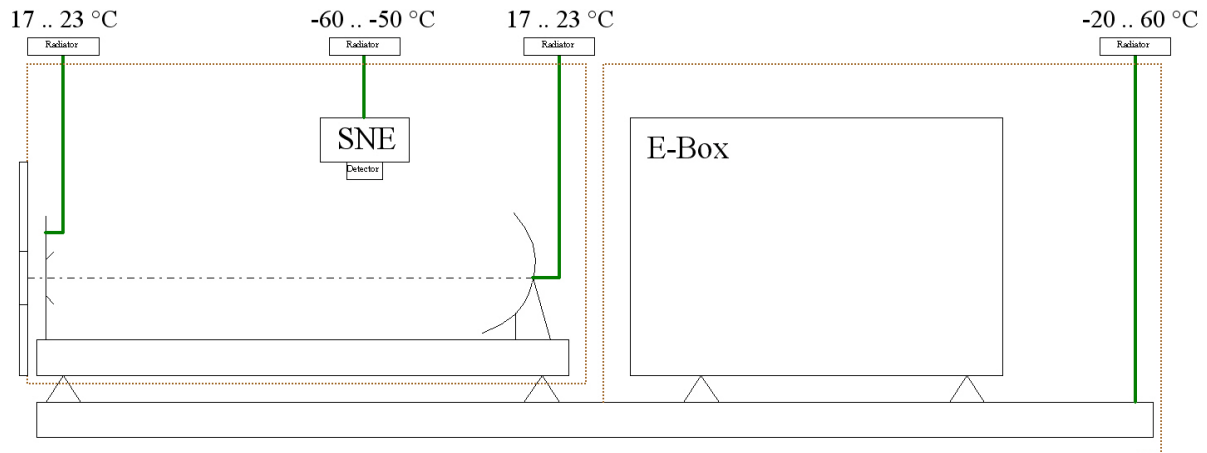


Figure 8-2: Principal TCS design.

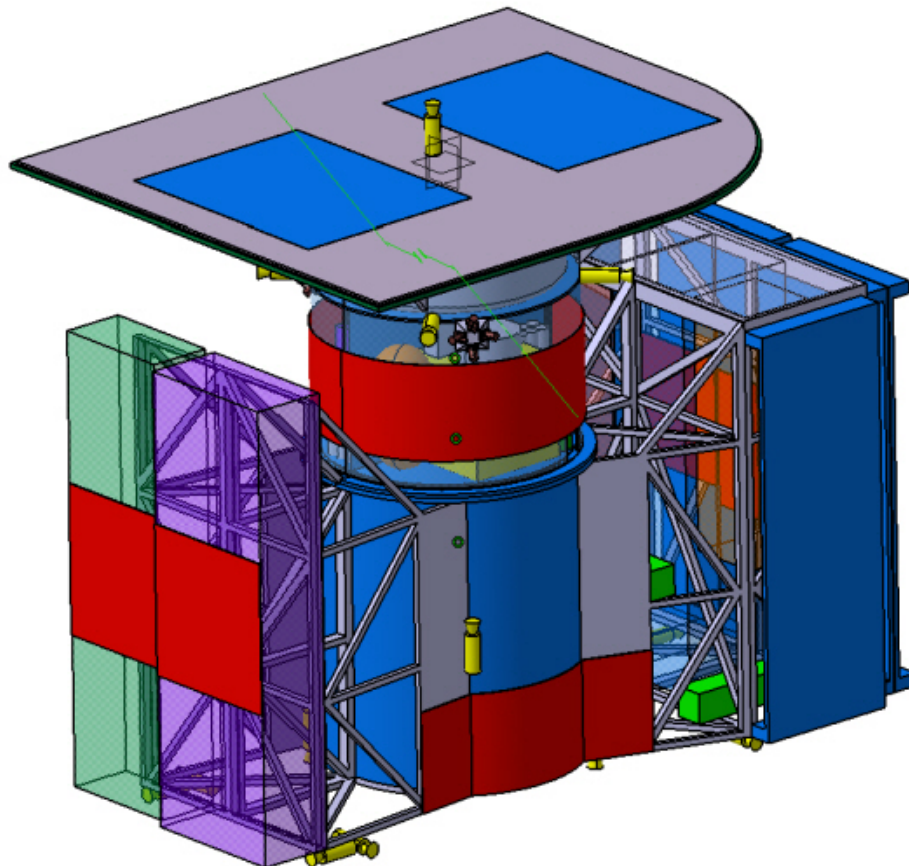


Figure 8-3: Both S/C with possible radiator areas (red coloured).

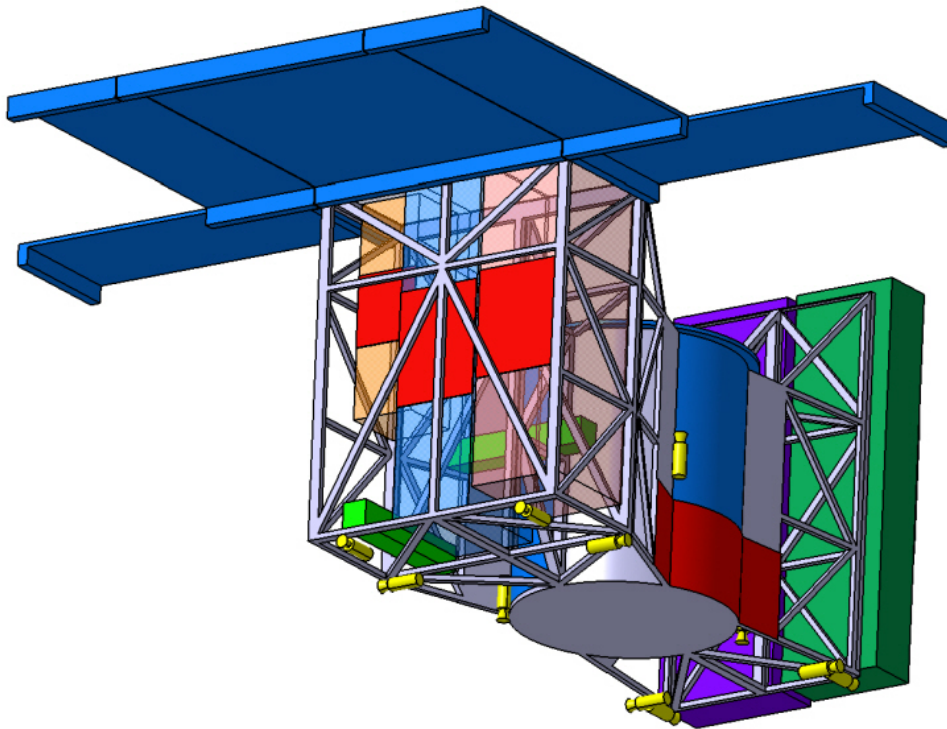


Figure 8-4: Possible radiator areas (red coloured) with deployed radiator solar arrays.

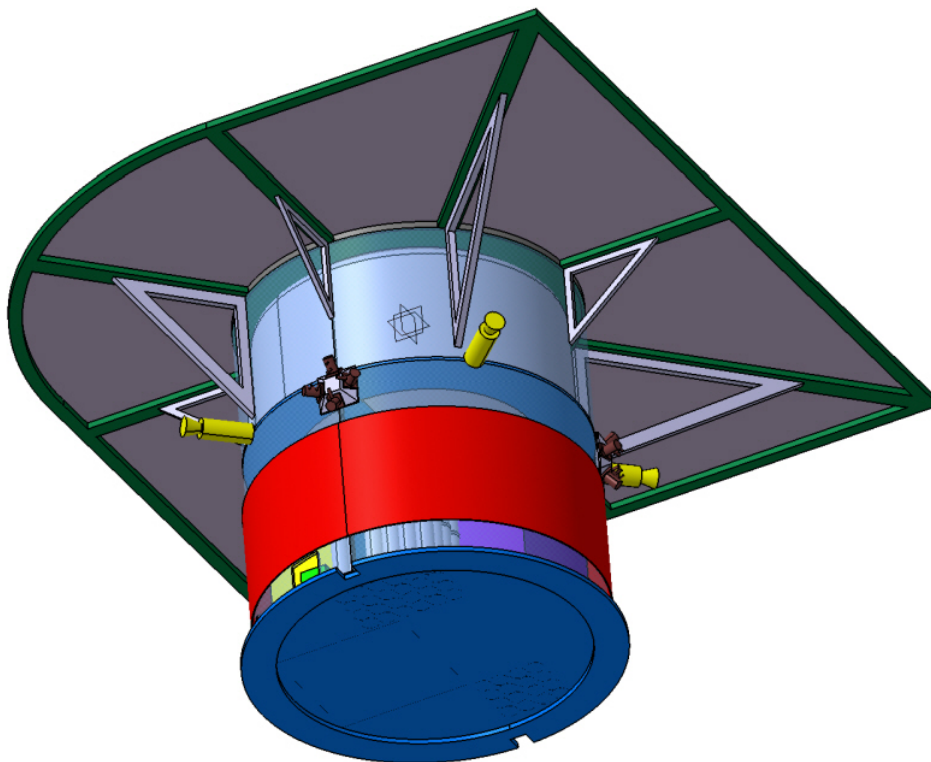


Figure 8-5: Possible radiator areas (red coloured) on the Occulter S/C.

For the Occulter S/C the radiation loads from the Coronagraph S/C must be considered. The instrument heaters must work during LM, TM, MM and SfM. The batteries heater will work mainly during the SfM.

8.3.1. List of Equipment Mass and Power Budget

Table 8-1, Table 8-2, Table 8-3 and Table 8-4 show the mass and power budget of the Thermal Control System.

Table 8-1: TCS mass budget of the Coronagraph S/C.

Element 1 neX Coronagraph Spacecraft			MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	Instrument MLI	5	1,0	To be modified	10	5,5
2	Instrument Radiator	7	0,3	To be modified	10	2,3
3	Instrument Emergency Heater	5	0,1	Fully developed	5	0,3
4	Battery Heater	1	0,2	Fully developed	5	0,2
5	S/C MLI	1	4,0	To be modified	10	4,4
6	Instrument Stand offs	15	0,2	To be modified	10	3,3
7	Radiator Stand offs	32	0,2	To be modified	10	7,0
8	SSM front plate surface	1	1,5	To be modified	10	1,7
9	S/C Radiator	1	0,4	To be modified	10	0,4
10	MLI stand offs	50	0,1	To be modified	10	5,5
11	T-Sensors	40	0,1	Fully developed	5	2,1
-	Click on button below to insert new unit		0,0	To be modified	10	0,0
SUBSYSTEM TOTAL		11	29,9		9,6	32,7

Table 8-2: TCS mass budget of the Occulter S/C.

Element 2 olmeX Occulter Spacecraft			MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	SSM front plate surface	1	2,0	To be modified	10	2,2
2	S/C MLI	1	1,5	To be modified	10	1,7
3	S/C Radiator	1	0,5	To be modified	10	0,6
4	MLI Stand offs	4	0,1	To be modified	10	0,4
5	T-sensors	5	0,1	Fully developed	5	0,3
6	Battery Heater	1	0,2	Fully developed	5	0,2
-	Click on button below to insert new unit		0,0	To be modified	10	0,0
SUBSYSTEM TOTAL		6	4,9		9,5	5,3

Table 8-3: TCS power budget of the Coronagraph S/C.

Element 1 neX Coronagraph Spacecraft			VER SPECIFICATION PER MODE				PPEAK AND POWER SPECIFICATION PER MOD					
Unit	Unit Name	Quantity	Ppeak	ScM			FAM			StM		
	Click on button above to insert new unit			Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)
1	Instrument MLI	5										
2	Instrument Radiator	7										
3	Instrument Emergency Heater	5	15,0	15,0	0,0	0,0	15,0	0,0	100,0	15,0	0,0	100,0
4	Battery Heater	1	20,0	20,0	0,0	0,0	20,0	0,0	0,0	20,0	0,0	50,0
5	S/C MLI	1										
6	Instrument Stand offs	15										
7	Radiator Stand offs	32										
8	SSM front plate surface	1										
9	S/C Radiator	1										
10	MLI stand offs	50										
11	T-Sensors	40										
-	Click on button below to insert new unit											
SUBSYSTEM TOTAL		11	95,0	95,0	0,0		95,0	0,0		95,0	0,0	

Table 8-4: TCS power budget of the Occulter S/C.

Element 2	olmeX Occulter Spacecraft		VER SPECIFICATION PER MODE				PPEAK AND POWER SPECIFICATION PER MOD					
Unit	Unit Name	Quantity	Ppeak	ScM			FAM			StM		
	Click on button above to insert new unit			Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)
1	SSM front plate surface	1										
2	S/C MLI	1										
3	S/C Radiator	1										
4	MLI Stand offs	4										
5	T-sensors	5										
6	Battery Heater	1	20,0	20,0	0,0	0,0	20,0	0,0	0,0	20,0	0,0	50,0
-	Click on button below to insert new unit											
SUBSYSTEM TOTAL		6	20,0	20,0	0,0		20,0	0,0		20,0	0,0	

8.4. To be studied / additional Consideration

Requirements from TCS to S/C structure are driven by the real configuration of the S/C components. Internal heat sources should be checked, necessary or undesirable thermal couplings should be worked in more detail, insulating stand-offs or simple conductors need to be dimensioned and the mounting and size of the radiators with respect to optimal viewing angles should be analyzed with a higher degree of accuracy. Solutions need to be found to locate the instrument radiators right next to the specimen to be cooled and also the way for Detector and SNE mounting. A thorough investigation of the thermal properties of the thermal bench and its thermal coupling to the S/C is necessary. Also the parameters of emergency heaters must be defined. The MLI configuration for the Coronagraph S/C and its instruments as well as for the Occulter S/C and a possible combination of the TCS of both S/C during the LM and TM must be studied.

Furthermore the system requirement to enable an uninterrupted observation of the sun needs clarification regarding the necessary length of observation that has to be allowed by the TCS. A new requirement must be defined, that each of the detectors must be into the temperature range of -50 to - 60 °C with a stability of 0.1 K for 10 min.

Future studies have to analyze, which area is required for each TCS and which positioning is the best. For these especially the outer radiation loads (q_{ext}) must be studied. On the solar disk

viewing side of the Coronagraph S/C the radiation loads from the solar panel back side q_{sp} will have a great impact of the efficiency of the radiators.

8.5. Summary

A group of TCS for the mission satellites and their instruments are manageable. The TCS will primarily consist of passive components like Multi-Layer-Insulation. Each instrument will furthermore be equipped with an own heater unit to enable a temperature stability in the required range for accurate scientific observation. Furthermore both S/C batteries will be equipped with heater units. All components need more thorough investigation.

9. Attitude and Orbit Control System

9.1. Introduction

SolmeX is a formation flying mission with very high relative and absolute pointing and position requirements. This makes the AOCS subsystem one of the most demanding subsystems on the SolmeX satellites. The AOCS is responsible for coarse sun acquisition in stacked configuration and during Safe Mode, for coarse relative positioning and absolute pointing during formation acquisition, maneuvers and orbit maintenance and precise relative positioning and absolute pointing in Science Mode.

The AOCS is similar to the planned Proba-3 mission. The formation flying aspect requires dedicated actuators and sensors that will be tested on Proba-3 and PRISMA and will be flight-proven after these missions.

The relative position control (formation keeping) is done by the Occulter S/C using a system of 12 cold-gas micro-thrusters. The system is also used for attitude control of the Occulter S/C. Rotation maneuvers around the z-axis are supported by a reaction wheel.

On the Coronagraph S/C attitude control is done using 4 reaction wheels in a tetrahedron configuration. The wheels have to be desaturated once a week. The hydrazine thruster system, which is also used for orbit maintenance will be used for that.

9.2. Pointing Requirements

In science Mode both spacecraft of SolmeX are separated by 200 m and the line connecting the center of Occulter and Coronagraph S/C must point to the Sun. The requirements are as follows:

- The distance between the spacecraft needs to be 200 m (TBC) +/- 10 cm (modified from 100 m to 200 m during the study)
- Lateral difference in position between the two spacecraft may not exceed +/- 1.0 mm

The pointing requirements read as follows (for instrument spacecraft):

- Pointing stability roll angle around axis Occulter - Coronagraph S/C: < 1 arcmin / 15 min
- Pointing stability: 0.2" / 20 min

9.3. Requirements and Design Drivers

Design drivers are clearly the high precision requirements for formation flying and pointing. Dedicated onboard sensors to measure relative position of the two spacecraft are needed. One for coarse relative position and attitude with 4 pi visibility during formation acquisition, maneuvers and orbit maintenance (Formation Flying Radio Frequency Sensor), a second one

with narrow FoV but precise relative distance measurement (Optical Metrology Sensor). A full AOCS for 3-axis stabilization is needed on each of the spacecraft with high accuracy on the Coronagraph S/C and lower accuracy on the Occulter S/C. In addition the Occulter S/C needs a 6 DoF micro-thruster system for relative position control.

9.3.1. List of Equipment Mass and Power Budget

Table 9-1 and Table 9-2 show the summary of the AOCS equipment for Occulter S/C and Coronagraph S/C. Table 9-3 and Table 9-4 list the power budget. The micro-thruster system with 12 cold gas thrusters is not mentioned, as it is shown in the summary of the propulsion system equipment. In addition coarse sun sensors with 4 pi visibility are needed for sun acquisition and safe mode. Due to small mass and negligible power consumption they are also omitted in the tables.

Table 9-1: AOCS mass budget of the Coronagraph S/C.

Element 1	SolmeX Coronagraph Spacecraft		MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	Gyrosscopes (ASTRIX 200 Fibre Optic Gyros)	1	10,0	Fully developed	5	10,5
2	StarTracker Camera (Terma)	2	1,0	Fully developed	5	2,1
3	StarTracker Processor (Terma)	2	1,2	Fully developed	5	2,5
4	FFRF	1	15,0	To be developed	20	18,0
5	Optical Metrology sensor	1	15,0	To be developed	20	18,0
6	Reaction Wheels (Bradford W18)	4	5,0	Fully developed	5	21,0
7	Reaction Wheel electronic	1	8,8	Fully developed	5	9,2
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		7	73,2		11,1	81,4

Table 9-2: AOCS mass budget of the Occulter S/C.

Element 2	SolmeX Occulter Spacecraft		MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	Gyrosscopes (muFors-1)	4	0,1	Fully developed	5	0,5
2	StarTracker Head (lower level accuracy)	2	1,1	Fully developed	5	2,3
3	StarTracker electronics (lower level accuracy)	0	0,0	Fully developed	5	0,0
4	FFRF	1	15,0	To be developed	20	18,0
5	Optical Metrology reflector	1	15,0	To be developed	20	18,0
6	Reaction Wheels (Bradford W18)	1	5,0	Fully developed	5	5,3
7	Reaction Wheels electronic	1	4,4	Fully developed	5	4,6
8	Reaction Wheel (Bradford W18, cold redundant)	1	5,0	Fully developed	5	5,3
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		7	47,1		14,6	54,0

The following existing and flight-proven components with appropriate performance have been assumed for calculation of dimensions and power and mass budgets:

- Star Tracker Coronagraph: Terma Star Tracker HE5-AS
- Gyrosscopes Coronagraph: EADS ASTRIX 200 fibre optic gyro
- Star Tracker Occulter: Vectronic Star Sensor Type VST-41M

- Gyroscopes: Litef Gyros muFors-1
- Reaction wheels (both Occulter and Coronagraph): Bradford Engineering RWA W18

The Formation Flying Radio Frequency sensor (FFRF) and the Optical Metrology System will be tested on PRISMA and Proba-3. Currently no datasheets exist and the values for power and mass are rough assumptions.

Table 9-3: AOCS power budget of the Coronagraph S/C.

Element 1	SolmeX Coronagraph Spacecraft		PPEAK AND POWER SPECIFICATION PER MODE						PPEAK AND POWER SPECIFICATION PER MODE						
Unit	Unit Name	Quantity	Ppeak	MM	MM	MM	ScM	ScM	ScM	FAM	FAM	FAM	SIM	SIM	SIM
	Click on button above to insert new unit			Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)	Pon (W)	Pstby(W)	Dc(%)
1	Gyroscopes (ASTRIX 200 Fibre Optic Gyros)	1	6,0	6,0	0,0	100,0	6,0	0,0	100,0	6,0	0,0	100,0	0,0	0,0	100,0
2	StarTracker Camera (Terma)	2	1,6	1,6	0,0	100,0	1,6	0,0	100,0	1,6	0,0	100,0	0,0	0,0	100,0
3	StarTracker Processor (Terma)	2	5,2	5,2	0,0	100,0	5,2	0,0	100,0	5,2	0,0	100,0	0,0	0,0	100,0
4	FFRF	1	15,0	15,0	0,0	100,0	0,0	0,0	100,0	15,0	0,0	100,0	0,0	0,0	100,0
5	Optical Metrology sensor	1	15,0	15,0	0,0	100,0	15,0	0,0	100,0	15,0	0,0	100,0	0,0	0,0	100,0
6	Reaction Wheels (Bradford W18)	4	63,0	63,0	17,0	25,0	63,0	17,0	5,0	63,0	17,0	5,0	63,0	17,0	5,0
7	Reaction Wheel electronic	1	0,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0
-	Click on button below to insert new unit														
SUBSYSTEM TOTAL		7	301,6	301,6	68,0		286,6	68,0		301,6	68,0		252,0	68,0	

Table 9-4: AOCS power budget of the Occulter S/C.

Element 2	SolmeX Occulter Spacecraft	Quantity	PPEAK AND POWER SPECIFICATION PER MODE						PPEAK AND POWER SPECIFICATION PER MODE						
Unit	Unit Name		Ppeak	MM Pon (W)	MM Pstby(W)	MM Dc(%)	ScM Pon (W)	ScM Pstby(W)	ScM Dc(%)	FAM Pon (W)	FAM Pstby(W)	FAM Dc(%)	SIM Pon (W)	SIM Pstby(W)	SIM Dc(%)
Click on button above to insert new unit															
1	Gyroscopes (muFors-1)	4	2,5	2,5	0,0	100,0	2,5	0,0	100,0	2,5	0,0	100,0	0,0	0,0	100,0
2	StarTracker Head (lower level accuracy)	2	2,5	2,5	0,0	100,0	2,5	0,0	100,0	2,5	0,0	100,0	0,0	0,0	100,0
3	StarTracker electronics (lower level accuracy)	0	0,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0
4	FFRF	1	15,0	15,0	0,0	100,0	0,0	0,0	100,0	15,0	0,0	100,0	0,0	0,0	100,0
5	Optical Metrology reflector	1	10,0	10,0	0,0	100,0	10,0	0,0	100,0	10,0	0,0	100,0	0,0	0,0	100,0
6	Reaction Wheels (Bradford W18)	1	63,0	63,0	0,0	100,0	63,0	17,0	5,0	63,0	17,0	5,0	0,0	0,0	100,0
7	Reaction Wheels electronic	1	0,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0
8	Reaction Wheel (Bradford W18, cold redundant)	1	0,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0	0,0	0,0	100,0
-	Click on button below to insert new unit														
SUBSYSTEM TOTAL			7	103,0	103,0	0,0	88,0	17,0		103,0	17,0		0,0	0,0	

9.3.2. Component Locations on SolmeX

On the Coronagraph S/C as well as on the Occulter S/C two redundant Star Trackers are needed. The LoS of the Star Trackers are perpendicular to the LoS of the Sun and to each other insuring that the Star Trackers are never blinded by the Sun during science mode. On the Coronagraph S/C they are mounted near the instrument with the highest performance requirement to avoid problems with structural vibrations and thermal variations of the structure. This is also the reason why the gyroscopes and the reaction wheels on the Coronagraph S/C should also be mounted in the same area.

The FFRF consists of 3 antennas and an electronic box on each spacecraft. The antennas are mounted on opposite edges of each spacecraft to have a good baseline for the measurement of the LoS to the other spacecraft.

The Optical Metrology System consists of a Dual Wavelength Laser Interferometer (DWI) and camera (CLS, coarse lateral sensor) on the one satellite and a retroreflector and an artificial star pattern on the other satellite. Both sensors have a very narrow FoV. The optical metrology system has to be mounted in such a way, that the retroreflector and the artificial star pattern on the one satellite is opposite to the DWI and the camera during science mode.

The 12 micro-thrusters will be mounted in 3 blocks with 4 thrusters per block on different sides of the Occulter S/C. The optimal configuration has to be studied in later phases of the project.

9.3.3. Performance Specifications

The lateral and longitudinal displacement of the two satellites during Science Mode is measured by the Optical Metrology System. The accuracy of this system is in the sub-mm range. This is sufficient to fulfill the requirements for longitudinal displacement (+/- 10 cm) and lateral displacement (+/- 1 mm).

For the measurement of the attitude in Science Mode the Star Trackers are used. They have a performance of < 5 arcsec (roll angle) and < 1 arcsec (other directions). By the combination of 2 Star Trackers mounted perpendicular to each other, an accuracy of < 1 arcsec in all directions can be reached. This alone is not sufficient to fulfill the pointing requirements. The data from the Star Tracker has to be filtered using the precise attitude rate information of the Fibre Optic Gyros. Only the estimated attitude as a result of the fusion of the different sensor data has a sufficient accuracy to fulfill the pointing requirement.

9.3.4. Mass and Power Budget

The mass budget of the components can be found in Table 9-1 and Table 9-2. The mass of the propellant for AOCS can be divided in propellant for reaction wheel desaturation on the Coronagraph S/C, formation keeping, attitude control and rotation maneuvers on the Occulter S/C.

The main disturbing force is the difference in solar radiation pressure (SRP) between the two satellites. For counteracting this force 6 kg cold gas is needed (50% margin, 6 years). For counteracting the SRP torque the same amount of cold gas is needed. The largest fraction of cold gas is required for rotation maneuvers around the z-axis which also include translational correction maneuvers in lateral direction. About 68 kg cold gas is needed for these maneuvers. So the total amount of cold gas needed on the Occulter S/C is 80 kg.

The hydrazine mass on the Coronagraph S/C to desaturate the reaction wheels due to SRP torque is 2.2 kg.

9.3.5. Disturbance Torques

Table 9-5 summarizes the various sources of disturbances and their strength as assumed for SolmeX during the course of the study.

Table 9-5: Disturbances occurring during SolmeX.

Disturbance	Strength
Differential SRP acceleration	1.33e-8 m/s ²
Differential SRP force	0.011 mN
SRP torque occulter	1.44e-5 Nm
Thruster force for counteracting SRP torque	0.010 mN
SRP torque coronagraph	3.87e-5 Nm
Reaction wheel angular momentum	23.4 Nms

9.3.6. Actuator Performance

To control the displacement the cold gas micro thrusters are used. The maximum thrust of the thruster should be 10 mN to perform a rotation maneuver around the z-axis within less than half an hour. As baseline the 10 mN pulsed cold gas thrusters from the Proba-3 mission are used. The accuracy reachable with this type of thrusters has to be studied in a later phase. If the accuracy is not sufficient, proportional thrusters with smaller maximum thrust have to be used in Science Mode. In this case, the rotation maneuver has to be performed by a different type of thrusters.

9.4. Reliability and Redundancy/ Risk

All components of the AOCS are flight proven and therefore TRL 9 except the micro-thrusters, the FFRF and the Optical Metrology System.

The baseline is to use 10 mN cold gas thrusters. These thrusters are flight proven and TRL 9. If smaller proportional thrusters are needed to fulfill the formation keeping and pointing requirements thrusters from three different suppliers are available with a TRL of 6 to 8.

The FFRF is tested at the moment on the PRISMA satellite. It can be considered TRL 8-9.

The Optical Metrology System will be tested on Proba-3. It can be considered TRL 5 at the end of phase B of Proba-3 (end of 2011).

9.5. To be studied / additional Consideration

The following issues need further analysis after the CEF-study:

- Detailed values for mass, power and dimensions of FFRF and Optical Metrology System
- Detailed accuracy calculation depending on thruster and choice of thruster types for different tasks (formation keeping and attitude control, rotation maneuvers, orbit maintenance)

- Optimization of thruster configuration
- Optimization of SRP pressure point versus CoG
- Accuracy calculation of sensor data fusion of gyro and Star Tracker data, maybe refinement of component choice
- Refinement of component placement

9.6. Summary

The AOCS of SolmeX is one of the most demanding subsystems due to the required precise formation keeping and attitude control. On the one hand sensors and actuators for attitude control are needed on both satellites. On the other hand dedicated sensors for relative position measurement have to be used for this mission. One satellite acts as master for formation keeping and uses a micro-thruster system to control the relative position.

In Science Mode both spacecraft of SolmeX are separated by 200 m and the line connecting the center of Occulter S/C and Coronagraph S/C must point to the sun with an accuracy of 10 cm (longitudinal) and 1 mm (lateral). The pointing stability has to be better than 1 arcmin in 15 min around the roll axis and 0.2 arcsec in 20 min in the other directions for the Coronagraph S/C.

The AOCS of SolmeX is similar to the one of the planned Proba-3 mission. The relative position control (formation keeping) is done by the Occulter S/C using a system of 12 cold gas micro-thrusters. The system is also used for attitude control of the Occulter S/C. Rotation maneuvers around the z-axis are supported by a reaction wheel.

On the Coronagraph S/C attitude control is done using 4 reaction wheels in a tetrahedron configuration. The wheels have to be desaturated once a week. The hydrazine thruster system which is also used for orbit maintenance will be used for that.

For attitude control both satellites use Star Trackers and gyroscopes. The data from these sensors has to be merged to reach an accuracy level needed to fulfill the pointing requirements. For the coronagraph spacecraft very precise Star Trackers (e.g. Terma Star Tracker HE5-AS) and gyroscopes (e.g. EADS ASTRIX 200 fibre optic gyro) have to be used. As the pointing requirements of the Occulter S/C are not as demanding as for the Coronagraph S/C less precise components with smaller mass and power consumption should be considered for the former.

The measurement of the relative position is done by the Formation Flying Radio Frequency Sensor (FFRF) and an Optical Metrology System. The FFRF uses 3 antennas on each satellite to emit a GPS-like signal for the measurement of the delay between the antennas. Knowing the delay between all antennas relative position and attitude can be computed with cm accuracy. The sensor has 4 pi visibility and is mainly used for formation acquisition, rotation maneuvers and during orbit maintenance.

The Optical Metrology System is the precise sensor for relative navigation in Science Mode. Using a Dual Wavelength Interferometer (DWI) and star tracker like camera on one satellite

and a retroreflector and an artificial star pattern on the second satellite the relative position can be measured with accuracy in the sub-mm level.

To control the attitude on the Occulter S/C 6 kg of cold gas is needed for 6 years (50% margin). Another 6 kg of cold gas is needed for formation keeping in science mode. The largest amount of cold gas, 68 kg, is needed to reposition the Occulter S/C relative to the Coronagraph S/C during a rotation maneuver around the z-axis. On the Coronagraph S/C 2.2 kg of hydrazine are needed for the desaturation of the reaction wheels.

10. Configuration

10.1. Requirements and Design Drivers

As already described before, SolmeX contains two dependent spacecraft in formation flying: the Occulter S/C and the Coronagraph S/C. To ensure the functionality of the instruments, the Occulter S/C has to provide/generate a shadow (umbra) onto the Coronagraph S/C with a required size and shape. This feature of ‘shadow generation and positioning’ is the main requirement and design driver for both spacecraft.

The Occulter S/C will be mounted on top of the Coronagraph S/C during launch and transfer. Therefore, an **adapter** for the Occulter S/C to the Coronagraph S/C as well as for the Coronagraph S/C to the launcher has to be considered. The circular shaped **launch adapter ring** lead to the chosen ‘tube design’ for the **main body** for both Coronagraph and Occulter S/C. This design also allows a simple conduction of the forces during launch.

Other important requirements are for example the orientation of AOC subsystems like the **Optical Metrology Reflector** and the **Formation Flying Radio Frequency Sensor (FFRF)**. Their reflectors and sensors have each a counterpart on the other S/C and thus have to be arranged in visibility to the other S/C so that they are pointing to each other. For the Occulter S/C it is positioned on the bottom side of the main body and on the Coronagraph S/C it is attached to the upper side of the main body. Thus it is secured that the instruments can point to each other.

The bus systems are mounted inside the main bodies (carbon fiber tube) of the S/Cs. For that, the following important requirements have to be additionally considered:

Reaction wheels:

For the AOCS reaction wheels are necessary. Four reaction wheels are mandatory for the Coronagraph S/C. They have to be accommodated parallel to the surfaces of a tetrahedral.

Star tracker:

Two star trackers are required on each S/C. The angle between them has to be 90°. Pointing to the sun is not allowed.

Batteries:

At least 72 batteries (type VES 100, see Chapter 7) have to be accommodated on the Coronagraph S/C, and 48 batteries on the Occulter S/C.

Solar Panel:

The Coronagraph S/C requires 5,5 m² (see Chapter 7.3.1), the Occulter S/C needs 2,6 m² solar array. Pointing to the sun is mandatory.

CUSP and VIRCOR:

The distance between the top ends of the instruments CUSP + VIRCOR to any other S/C structure have at least to be 200 mm. Otherwise the structure would influence the payload.

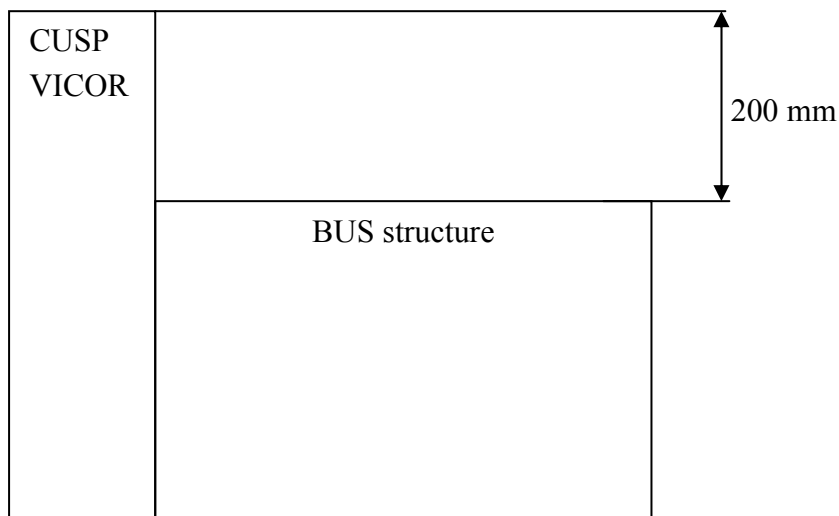


Figure 10-1: CUSP and VIRCOR position requirement.

Further requirements are given below in Chapter 11.

10.2. Baseline Design

10.2.1. Coronagraph Spacecraft

Figure 10-2 depicts the configuration of the S/C's subsystems and instruments within the Coronagraph S/C structure.

10.2.2. Occulter Spacecraft

Figure 10-3, Figure 10-4 and Figure 10-5 depict the configuration of the S/C's subsystems and the occulter frame within the Occulter S/C structure.

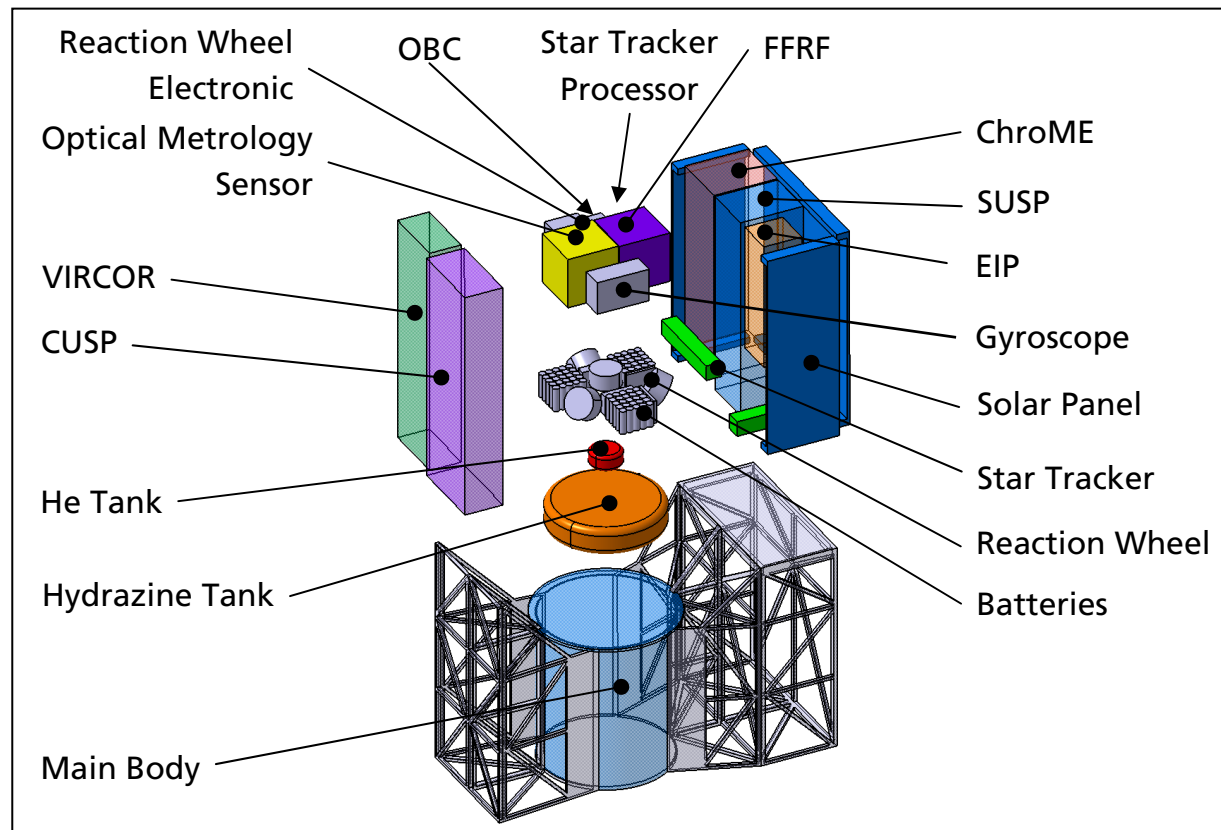


Figure 10-2: Coronagraph S/C baseline design.

Occulter S/C Structure Mass:
138kg

S/C Dimensions:
2110 x 2435 x 1030 (1415) mm³

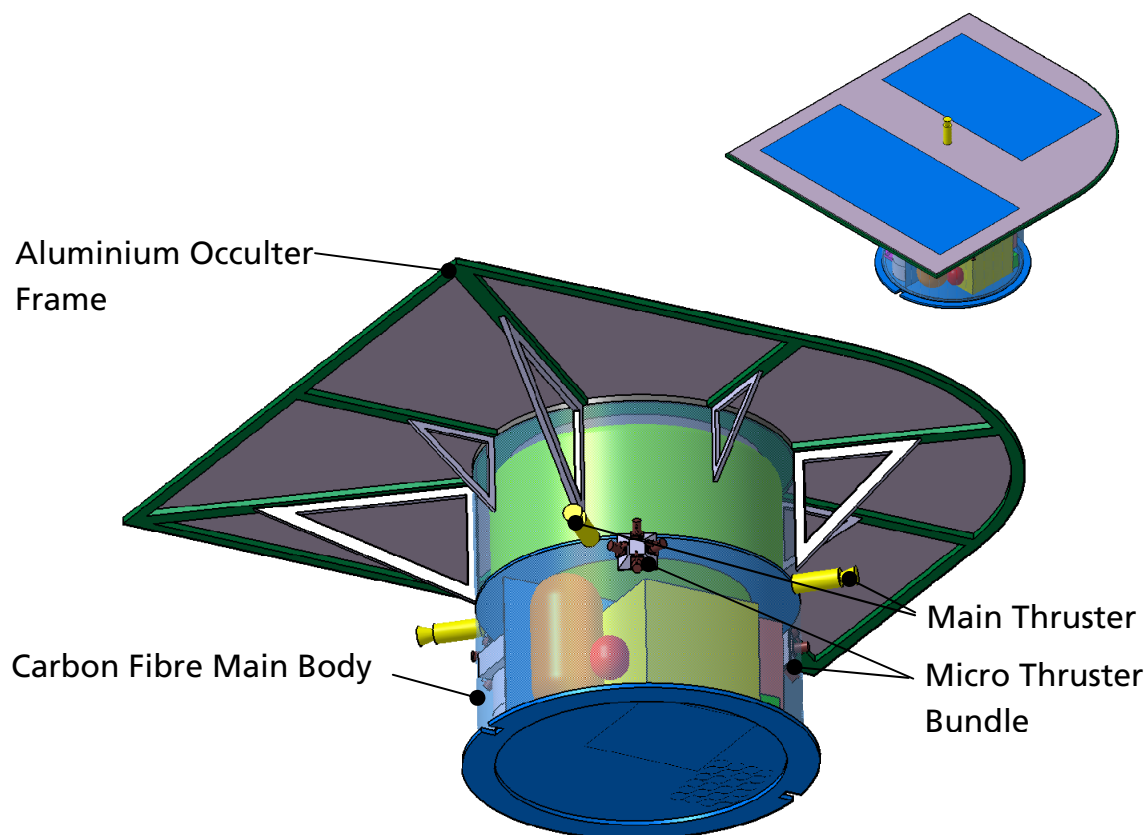


Figure 10-3: Occulter S/C baseline design

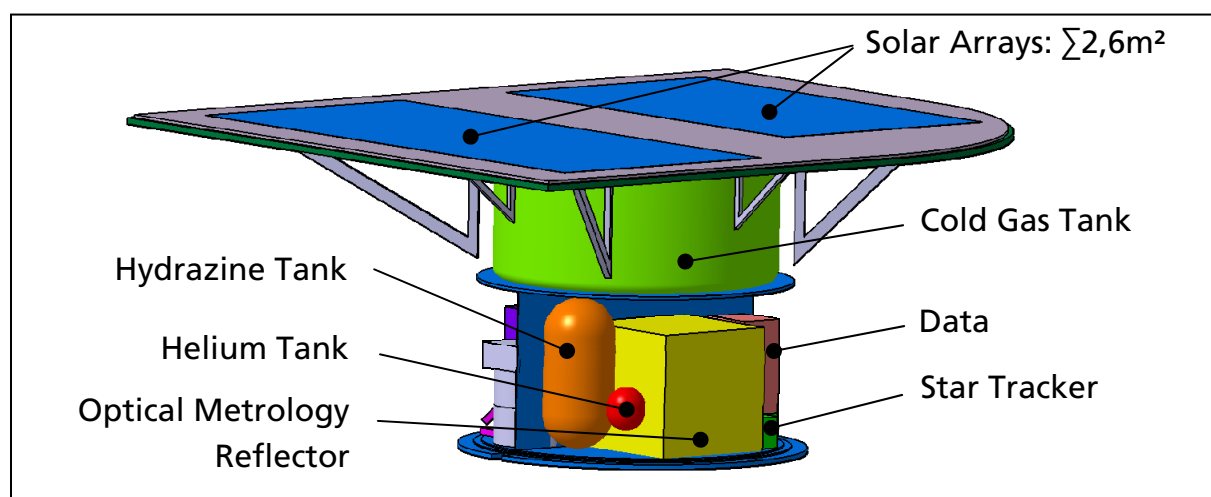


Figure 10-4: Occulter S/C configuration side 1

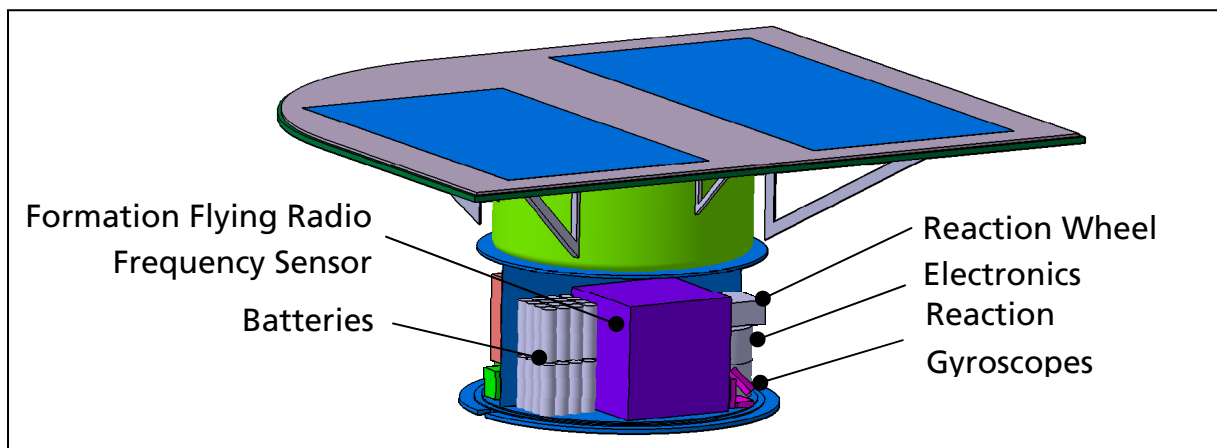


Figure 10-5: Occulter S/C configuration side 2

10.3. To be studied / additional Consideration

Thruster positioning needs further optimization regarding AOCS requirements and consideration regarding effects of exhaust plumes on the Coronagraph S/C instruments. At the end of the CE study, the total area for solar cells had to be enlarged (from 3.5 m² up to 5.5 m²). To reach this requirement, two additional solar panels will be connected to the deployable solar panels.

With consultation of the thermal subsystem responsible subsequent to the CE study, additional radiators were added to the Occulter and Coronagraph S/C structure and to the instruments. Figure 10-6 shows the current configuration of the Coronagraph S/C with additional solar panels, radiators and thrusters; Figure 10-7 depicts the configuration of the Occulter S/C with the radiators on the tube barrel.

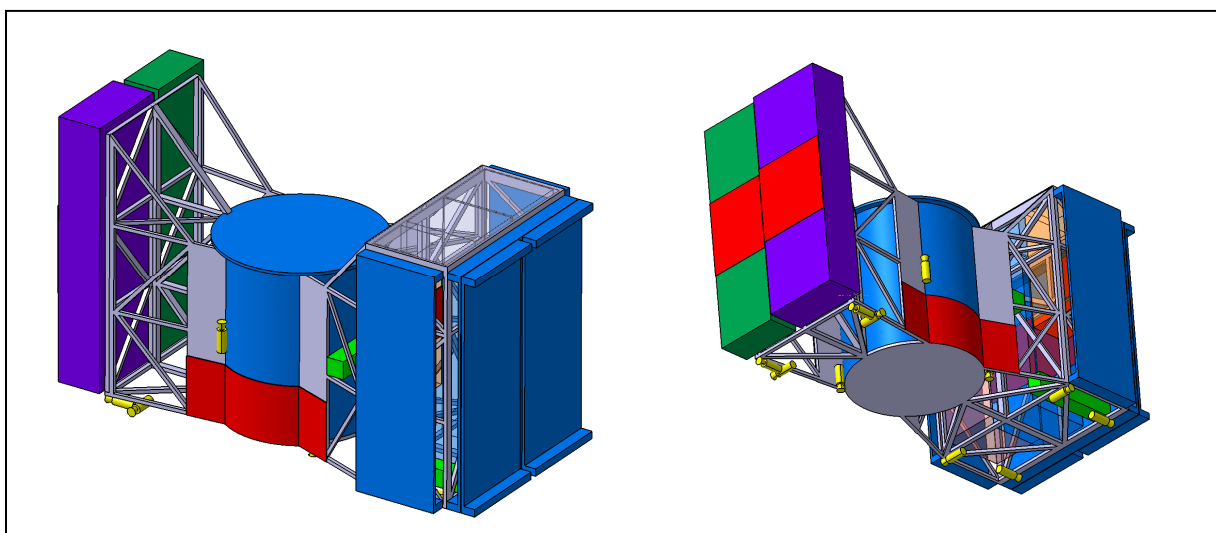


Figure 10-6: Coronagraph S/C configuration for thruster, solar panels and radiators

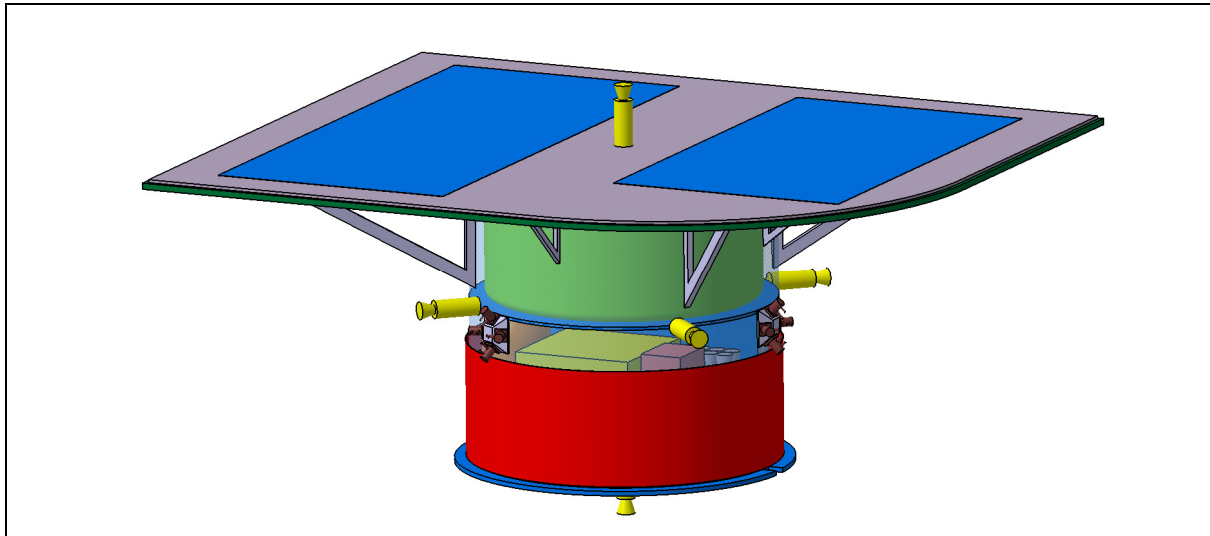


Figure 10-7: Occulter S/C configuration for radiator

The current designs of the Coronagraph S/C and the Occulter S/C do not include any kind of antennas neither for communication nor for the AOC subsystem. The positioning has to be studied further.

The suggested possibility to replace the actual cold gas tank on the Occulter S/C when using an electrical propulsion system has to be studied by the propulsion subsystem responsible. This would save mass and downsize the Occulter S/C. The replacement would be possible if the unused sun pointing area on the occulter frame suffices to generate enough power for the additional electrical propulsion system.

10.4. Summary

To ensure the function and operation of the required optical instruments a spacecraft design with two separate spacecraft in formation flying is necessary; the Coronagraph S/C as instrument carrier and the Occulter S/C for casting a shadow onto the former S/C (and with that assuring the functionality of the required instruments). The launcher adapter ring ‘determines’ the design for the S/Cs main bodies, so a tube shape is chosen for both S/Cs, which further supports load conduction within the spacecraft structure.

S/C subsystems are in each case accommodated in the mentioned tube shaped main bodies, aside from thrusters for propulsion and AOCS and from radiators which are mounted to the outer face of the main bodies and S/C structures. Antennas have not been considered for the configuration during the study.

The Occulter S/C carries the solar panels on the shadow generating, sun pointing occulter frame. The Coronagraph S/C is accommodated with deployable solar panels.

11. Structure incl. Mechanisms

11.1. Requirements and Design Drivers

The S/Cs have to fit into the circular shaped launcher fairing of the Soyuz Fregat. The diameter is 3.86 m. The mission requires five optical instruments that should be accommodated on the Coronagraph S/C, two of them in the umbra and three outside the penumbra in a sun illuminated area. The distance between the outer edge of the umbra and the end of the penumbra is 2 m. This has to be considered for the structural design of the Coronagraph S/C.

Additionally, it is required to provide the mounting of the required area of solar panels on the Coronagraph S/C. The size of the total area for solar cells on the Coronagraph S/C was considered with 3.5 m² at the beginning of the structural development, increased to 5.5 m² at the study's end.

A light weight structure is of course mandatory for the design of the S/Cs' structures.

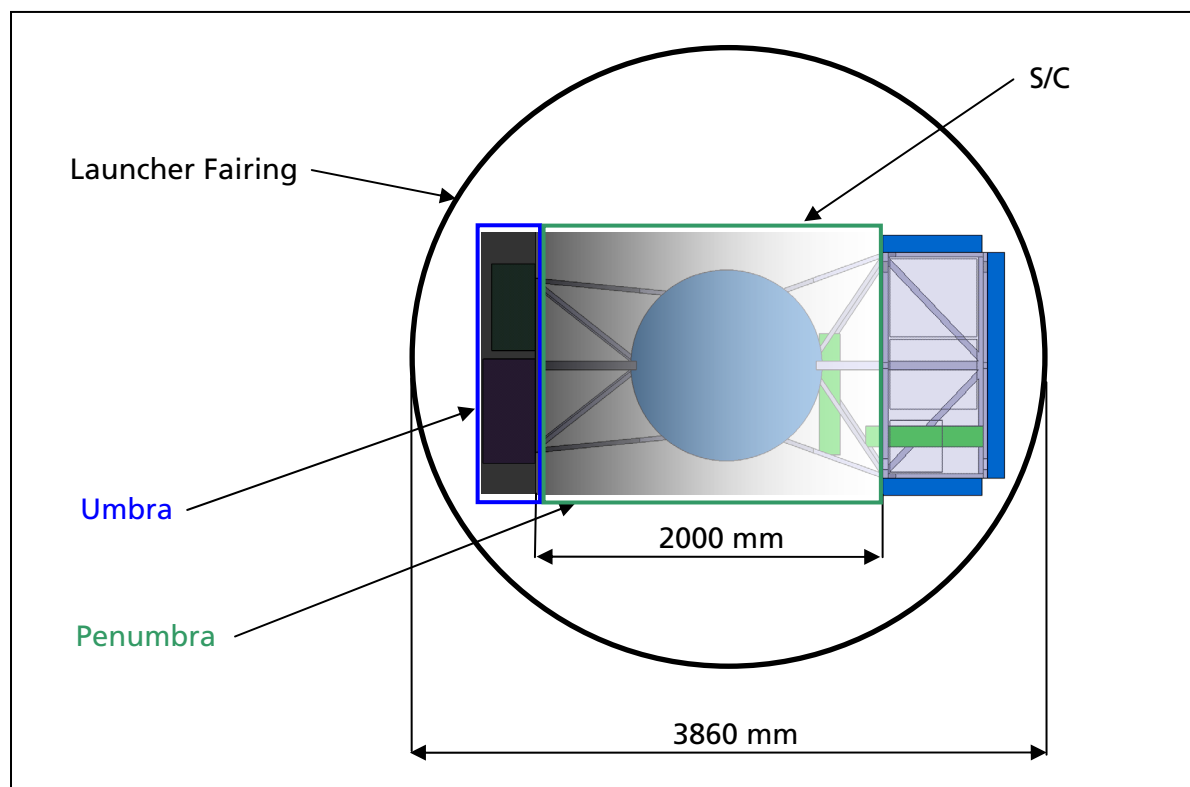


Figure 11-1: S/C - Launcher configuration and consequential requirements.

11.2. Options and Trades

During the design process it was discussed, where the solar panels should be mounted. Basically there are two ways to accommodate the solar panels. In option one the solar panels are connected to the main structure by a framework. This configuration shifts the centre of gravity (CoG) next to the centre of rotation and it is possible that the solar pressure point is closer to the CoG. Both effects lead to a reduced amount of energy used for AOCS. For the second option the solar panels are connected to the main structure directly. The main driver for this configuration is a simple and light connection to the structure. Both options are depicted in the sketch below (Figure 11-2). From the structure development point of view, option two is the better choice. One of the reasons is the simple deployment of the solar cells. In Option 1 a framework has to be designed to keep the solar panels out of the shadow produced by the Occulter S/C. That framework has to be as long as the main S/C. The huge dimensions would increase the total mass significantly.

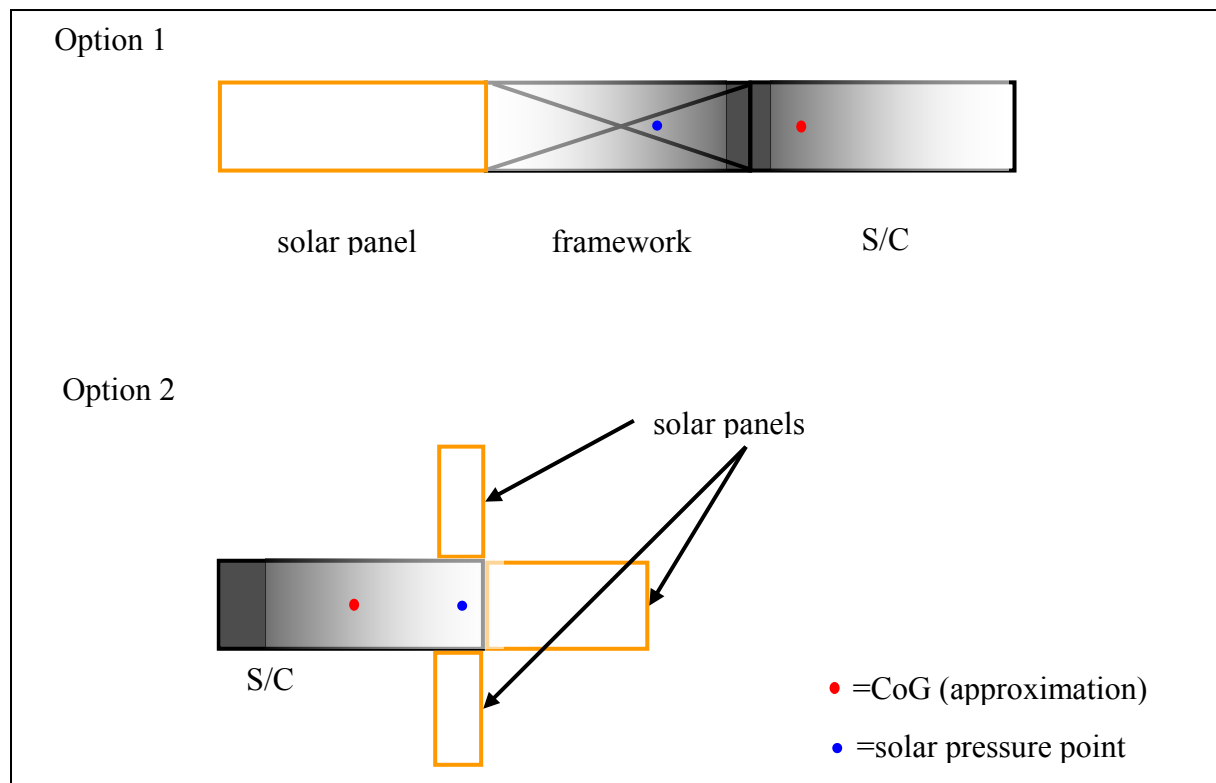


Figure 11-2: Coronagraph S/C structure options.

Further investigations show, that the solar pressure point of Option 1 is as far away from the CoG as in Option 2. Further, the mass of the P/L and the bus system is so large that the CoG can only be slightly moved. The result of the investigation is that the total amount of energy used for AOCS is as large in Option 1 as in Option 2. With respect to the structural problems resulting by Option 1, Option 2 was chosen.

11.3. Baseline Design

The current Coronagraph S/C consists of a carbon fiber tube and an aluminum framework. The tube shape as the main body was chosen because of the circular shaped launch adapter ring. Due to the fact that the Occulter S/C will be mounted on top of the tube it is useful to conduct the force as simple as possible. The tube shape was also chosen to derive the forces resulting by a movement of the instruments directly.

A framework is considered as the connection between the P/L instruments and the main body because it is the easiest and lightest opportunity to connect the different parts. For the first design iteration the framework is made of aluminium.

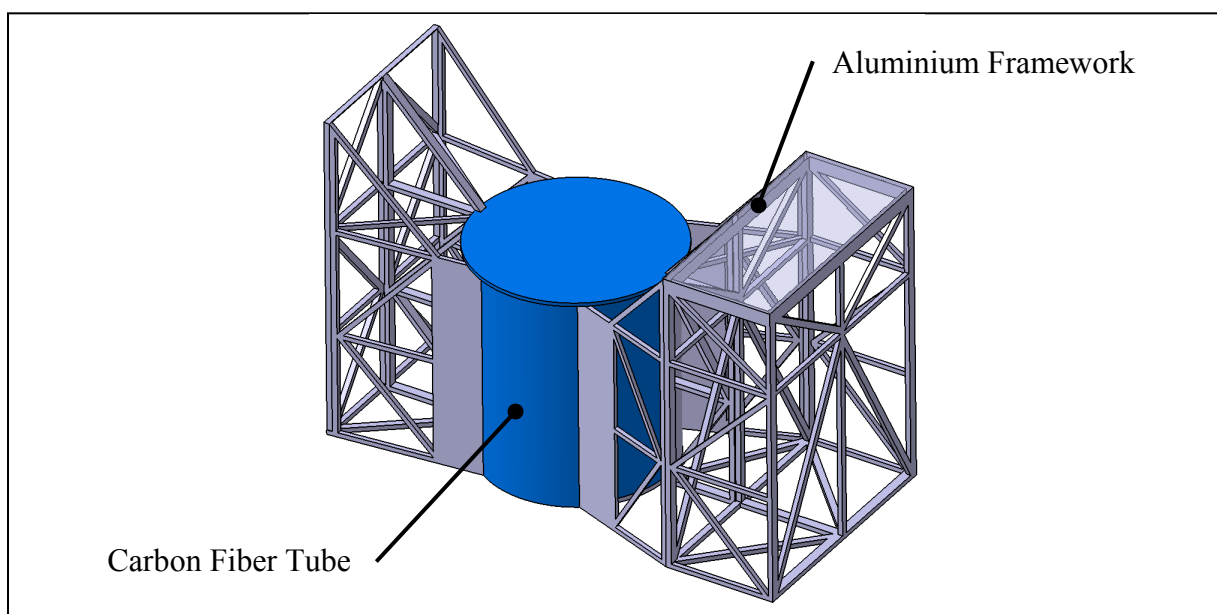


Figure 11-3: Baseline design - Coronagraph S/C structure

11.3.1. List of Equipment Mass Budget

The following two tables (Table 11-1 and Table 11-2) list the structural elements of both spacecraft Coronagraph S/C and Occulter S/C.

Table 11-1: Structure mass budget for the Coronagraph S/C.

Element	Total mass [kg]
Aluminium framework	314
Carbon fibre tube	88
Total	402

Table 11-2: Structure mass budget for the Occulter S/C.

Element	Total mass [kg]
Aluminium occulter frame + frame holder	66,4
Occulter top panel (sandwich)	4,5
Carbon fibre tube	42,7
Carbon bottom and inner plate	24,3
Total	137,9

11.4. To be studied / additional Consideration

It should be discussed to replace some parts of the aluminium framework of the Coronagraph S/C and the aluminium frame holder of the Occulter S/C by carbon fiber tubes. That will reduce the total structural mass significantly. If it is not possible to use carbon fiber tubes, the mass can also be reduced by replacing the current aluminium bars by aluminium hollow profiles.

In the current designs stiffeners inside the tubes are not considered. For the design it is recommended to include different stiffeners because of the high loads during launch. From accommodation point of view these stiffeners can be used as an opportunity to mount the subsystems.

After finishing the structure design it is necessary to make finite element analysis to proof the suitability of the chosen dimensions.

11.5. Summary

During the study it was possible to develop a detailed structural design. For both spacecraft it is possible due to the combination of a tube shaped main body (carbon fibre) and a framework (aluminium) to decrease costs by using simple structural elements and to reduce mass by using composite materials. The current dimensions are the product of engineering experience. Further analyses have to confirm the reliability of the structures.

12. Propulsion

12.1. Requirements and Design Drivers

The main driver for the selection of a propulsion system is the ΔV that has to be achieved during the mission. The SolmeX mission requires a total ΔV of 129.42 m/s which contains 65 m/s for the transfer, to be generated for the whole S/C, and 60 m/s for orbit maintenance that has to be generated by each spacecraft, the Coronagraph [Element1] and the Occulter [Element2], separately. Further on, the propulsion system has to allow formation keeping in the Libration point orbit and reaction wheel desaturation.

This yields to the specification of the propellant, propellant mass, the tanks and thrusters. The mission's ΔV -requirements are summarized in Table 12-1.

Table 12-1: The required ΔV s for the two spacecraft of the SolmeX mission, the Coronagraph S/C (EI 1) and the Occulter (EI 2).

Usage	ΔV	Spacecraft
Orbit insertion at L_1	65 m/s	Coronagraph S/C and Occulter S/C in stack
Orbit maintenance 10 m/s per year for 3 + 3 years	60 m/s	Coronagraph S/C
Desaturation of Reaction Wheels	4.42 m/s	Coronagraph S/C
Orbit maintenance 10 m/s per year for 3 + 3 years	60 m/s	Occulter S/C
Total ΔV to be covered by Element I thrusters	129.42 m/s	-

12.2. Options and Trades

Formation flying requires only one spacecraft with a highly accurate attitude control system as only the relative position requires high accuracy and this can be controlled by a single spacecraft.

In a first draft, the accurate attitude control system was assumed to be mounted onto the Coronagraph S/C. Since the Coronagraph S/C's mass is about three times larger than the Occulter S/C's, however, the needed propellant mass for the Coronagraph for attitude control was twice as high as for the Occulter S/C. Therefore the accurate attitude control system was rearranged and designed for the Occulter S/C, which resulted in a mass reduction of 160 kg regarding the launch mass. A further mass reduction of 123 kg was achieved by minimizing the needed ΔV from initially 260 m/s down to 125 m/s (as given in Table 12-1) by changing the transfer orbit and the resulting orbit amplitude around L_1 (further information see Chap. 3.2).

12.3. Baseline Design

12.3.1. Thrusters

For orbit maintenance the 10N ‘CHT 10’ Thrusters, manufactured by EADS Astrium, were chosen. They have a total impulse of 100.000 Ns and a specific vacuum impulse of up to 230 s. The thrusters can be used for the Coronagraph S/C as well as for the Occulter S/C for maintaining orbit. Overall the Occulter S/C has twelve proportional micro thrusters, manufactured by Bradford Engineering, for station keeping (the vacuum impulse for the PMTs is $I_{sp} = 60$ s and the nominal thrust is $F_n = 10$ mN) and six ‘CHT 10’ thrusters for orbit maintenance. The coronagraph instead has twelve ‘CHT 10’ thrusters, the additional six thrusters are used for desaturation of the reaction wheels. The properties of the thrusters are listed in Table 12-2 and depictions can be found in Figure 12-1.

Table 12-2: Summary of the properties of the thrusters used for SolmeX’ two spacecraft.

Thruster	Type	Quantity	Thrust	Specific Impulse
CHT 10 (Astrium)	Hydrazine	CS: 12 OS: 6	10 N	230 s
PMT (Bradford)	Cold Gas	OS: 6	10 mN	60 s

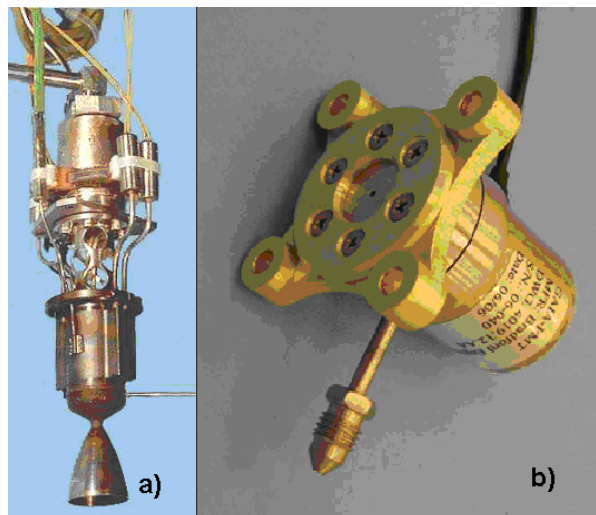


Figure 12-1: The two thruster types used for the SolmeX mission: a) CHT 10 by EADS Astrium b) Proportional Micro Thruster by Bradford

12.3.2. Propellant Tanks

For all tanks a titan composite was chosen to allow a large tensile strength of the material in combination with a low mass. The hydrazine (N_2H_4) tank for the Coronagraph S/C has a total

mass of 29.63 kg and contains a volume of 113.75 litres N_2H_4 including a margin of 7% to accommodate losses due to leakage and residue in valves, etc. at the end of the operation. The Occulter S/C is equipped with two tanks, one for the N_2H_4 and one for the cold gas (N_2). The former has a total mass of 12.13 kg and contains a total volume of 16.13 litres. Because the cold gas tank needs a pressure of 300 bar to store the N_2 , the tank composite needs to be thicker, which yields to a total mass of 113.82 kg. As before, both tanks are calculated with a 7% margin for none usable propellant.

12.3.3. Pressurisation System

The N_2H_4 -Tanks (Coronagraph and Occulter S/Cs) have a helium pressurisation system, which is also to be manufactured of a titan composite. The Coronagraph requires 0.47 kg of helium for pressurization and thus a tank with a volume of 8.09 litres and a total tank mass of 1.147 kg. For the Occulter S/C the need of 0.067 kg helium yields to a tank volume of 1.14 litres and a total tank mass of 0.763 kg.

12.3.4. Piping Plan

The piping plans for both spacecraft are presented in Figure 12-2 and Figure 12-3, respectively for the Occulter and the Coronagraph S/C.

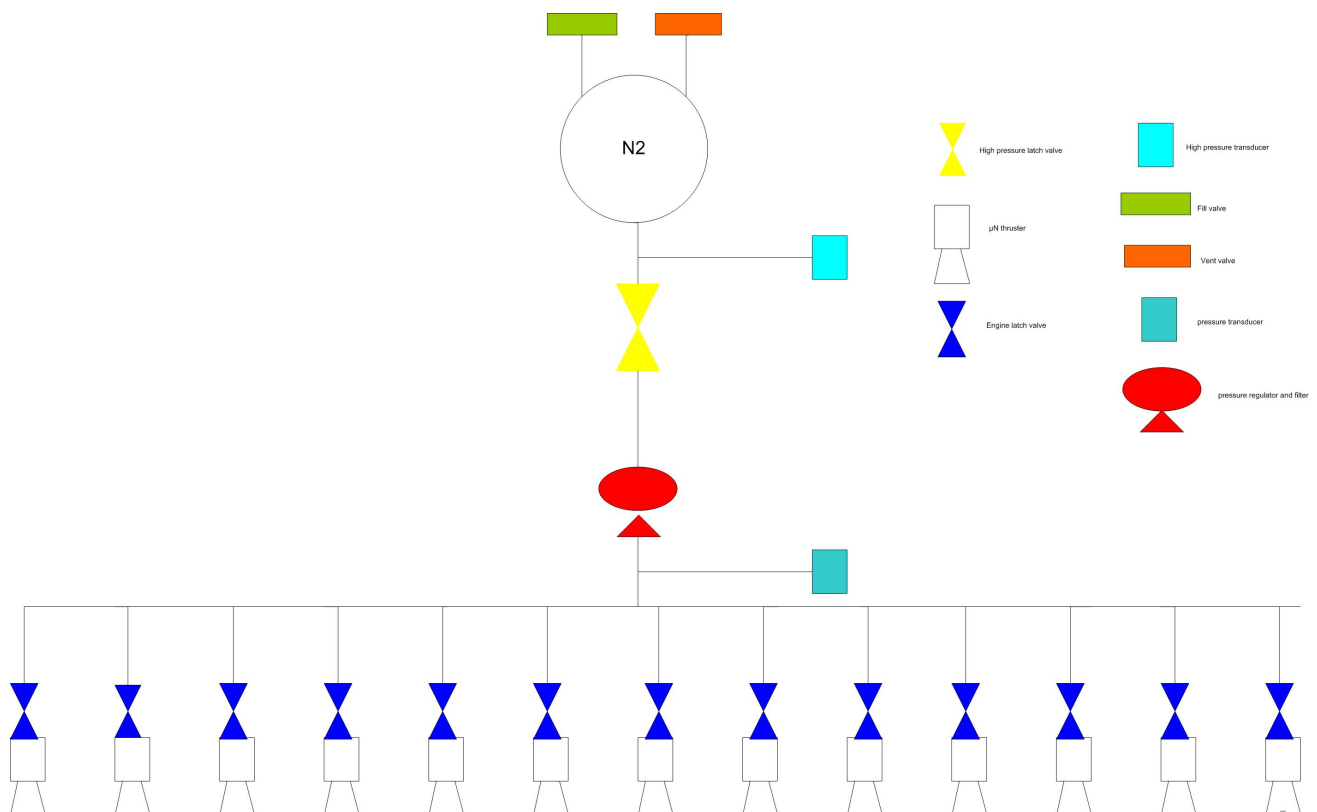
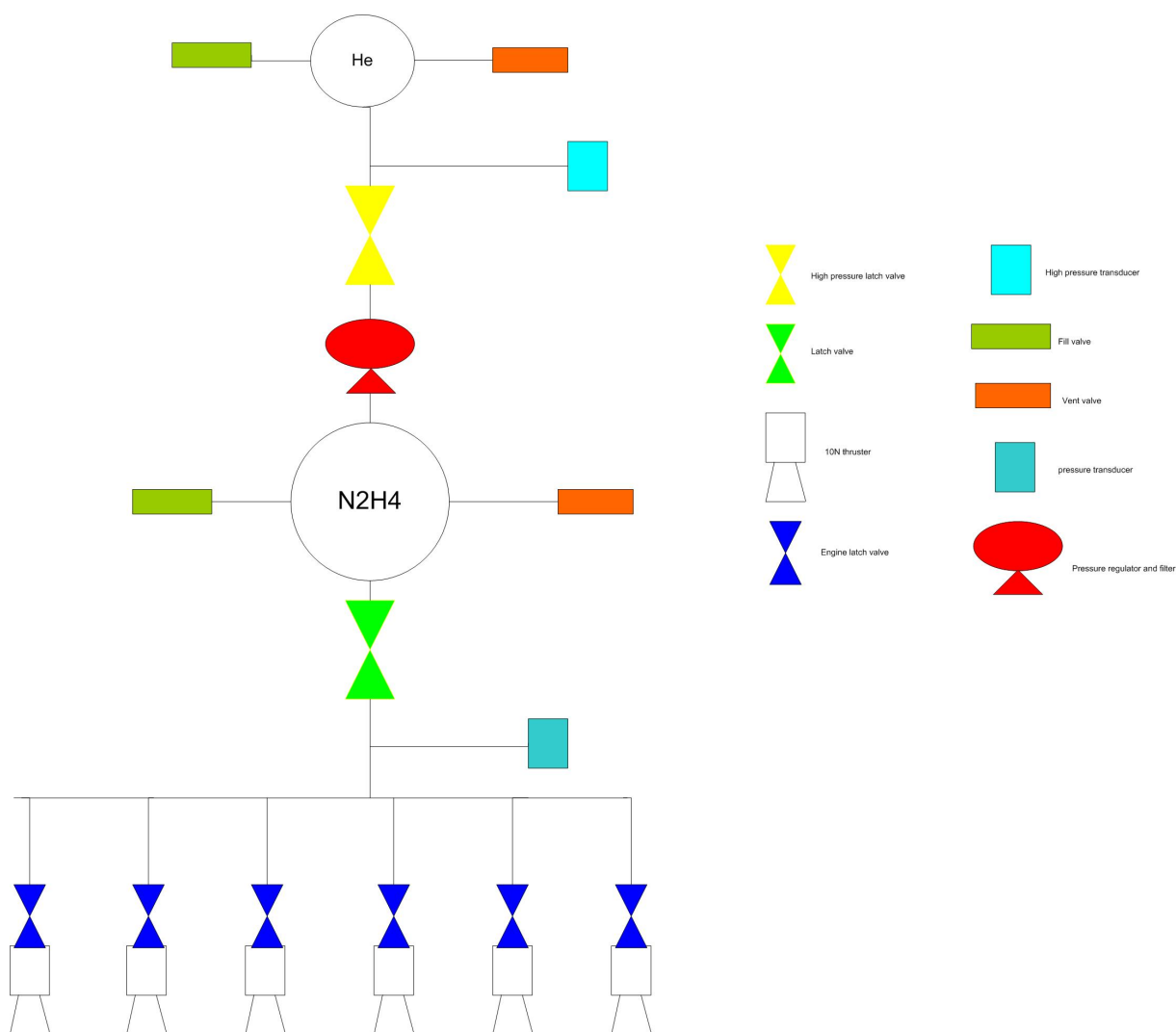


Figure 12-2: The piping plan for the Occulter S/C's Attitude Control System.



12.3.5. List of Equipment Mass and Power Budget

Tables 12-3 to 12-6 list the mass and power budgets of the propulsion system components as used by SolmeX.

Table 12-3: Mass budget for the Coronagraph S/C's propulsion system.

Element 1 meX Coronagraph Spacecraft			MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	CHT 10 Thruster	12	0,2	To be developed	20	3,5
2	N2H4 Tank	1	29,6	To be developed	20	35,6
3	Helium Tank	1	1,1	To be developed	20	1,4
4	He pressuration	1	0,5	To be developed	20	0,6
5	Heater	1	0,1	To be developed	20	0,1
6	Valve	1	0,1	To be developed	20	0,1
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		6	34,3		20,0	41,2

Table 12-4: Mass budget for the Occulter S/C's propulsion system.

Element 2	-		MASS [kg]			
Unit	Unit Name	Quantity	Mass per quantity excl. margin	Maturity Level	Margin	Total Mass incl. margin
	Click on button above to insert new unit					
1	Helium Tank	1	0,8	To be developed	20	0,9
2	Propellant Tank	1	12,1	To be developed	20	14,6
3	CHT 10 Thruster	6	0,2	To be developed	20	1,7
4	Cold Gas Tank	1	113,8	Fully developed	5	119,5
5	N2 Propellant	1	0,0	To be developed	20	0,0
6	He pressurization	1	0,8	To be developed	20	0,9
7	N2 thruster	12	0,2	Fully developed	5	2,5
8	N2H4 Heater	1	0,1	To be developed	20	0,1
9	N2H4 Valve	1	0,1	To be developed	20	0,1
-	Click on button below to insert new unit		0,0	To be developed	20	0,0
SUBSYSTEM TOTAL		9	131,5		6,7	140,4

Table 12-5: Power budget for the Coronagraph S/C's propulsion system.

Element 1	meX Coronagraph Spacecraft		P _{PEAK} AND POWER SPECIFICATION PER MODE								
Unit	Unit Name	Quantity	P _{peak}	LM			TM			MM	
	Click on button above to insert new unit			Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby
1	CHT 10 Thruster	12	20,0	18,0	2,0	0,0	18,0	0,0	0,0	5,0	0,0
2	N2H4 Tank	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
3	Helium Tank	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
4	He pressurization	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
5	Heater	1	6,4	6,0	2,0	0,0	6,0	2,0	0,0	5,0	0,0
6	Valve	1	6,5	6,0	2,0	0,0	6,0	2,0	0,0	5,0	0,0
-	Click on button below to insert new unit										
SUBSYSTEM TOTAL		6	252,9	228,0	28,0		228,0	4,0		70,0	0,0

Table 12-6: Power budget for the Occulter S/C's propulsion system.

Element 2	-		P _{PEAK} AND POWER SPECIFICATION PER MODE								
Unit	Unit Name	Quantity	P _{peak}	LM			TM			MM	
	Click on button above to insert new unit			Pon	Pstby	Dc	Pon	Pstby	Dc	Pon	Pstby
1	Helium Tank	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
2	Propellant Tank	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
3	CHT 10 Thruster	6	20,0	18,0	2,0	0,0	18,0	6,0	0,0	0,0	0,0
4	Cold Gas Tank	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
5	N2 Propellant	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
6	He pressurization	1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
7	N2 thruster	12	4,5	5,0	2,0	0,0	5,0	0,0	0,0	5,0	0,0
8	N2H4 Heater	1	6,4	6,0	2,0	0,0	6,0	2,0	0,0	0,0	0,0
9	N2H4 Valve	1	6,5	6,0	2,0	0,0	6,0	2,0	0,0	0,0	0,0
-	Click on button below to insert new unit										
SUBSYSTEM TOTAL		9	186,9	180,0	40,0		180,0	40,0		60,0	0,0

12.4. Additional Consideration

Further optimization of the subsystem mass on both spacecraft should be the task for further development. A significant amount of mass reduction can be achieved by optimization of the

propellant tanks and the attitude control thrusters. Since the volume of a propellant tank is set by the amount of propellant needed the only option to reduce mass is adaption of tank shape. Several combinations are possible e.g. spherical, cylindrical, tubes or even a combination of two spheres and two tubes between the spherical tanks. This optimization requires also significant consideration regarding spacecraft configuration.

By changing the AOC thrusters, the required propellant and tank mass can be reduced by up to 75% for attitude control. The only alternative for cold gas as an attitude control thruster are electrical thrusters, because the thrust of a liquid propellant like hydrazine is too large. However, as ion thrusters need 5 kW power they are currently not a feasible option for SolmeX.

Pulsed Plasma Thrusters or Resistojet are the most likely alternatives for cold gas thrusters. Both have the lifetime and also the total impulse and small thrust (0 - 100 mN) required for attitude control, but need 200 W of power to operate, which would result in an increase of the overall power demand. Therefore a possible trade-off needs to be made between the reduction of propellant mass and the increase of power generator mass in case of usage of electrical engines.

12.5. Summary

The current SolmeX mission profile requires a ΔV of 65 m/s for orbit insertion. These will be covered by the Coronagraph S/C's 12 'CHT10' thrusters ($I_{sp} = 225$ s). The 10 N thrusters will use 123 kg of hydrazine as propellant which requires a 43 kg tank. In addition these thrusters will also be used for orbit maintenance – which requires a ΔV of 60 m/s for each spacecraft for 6 years – and for desaturation of the reaction wheels.

The Occulter S/C uses six 'CHT10' thrusters for orbit maintenance and uses twelve proportional micro thrusters for formation keeping. The PMTs ($I_{sp} = 50$ s) need 80 kg of Nitrogen as propellant and a 114 kg tank to store it. The propulsion system mass is thus about 360 kg.

13. Cost Analysis

13.1. Introduction

Three main cost estimation methodologies can be applied to obtain a cost estimate for a mission during the various mission phases. These methodologies are “Engineering Build-Up” (Bottom-Up), “Analogy cost estimation” and “Parametric cost estimation”. All of the latter techniques are directly correlated with the different demands of a variety of projects in their respective mission phases.

In order to obtain a relevant, indicative and valid cost estimate for a mission, it is essential to identify the most appropriate cost estimation approach on a case to case basis. It is then essential to select a tool/model which can be applied.

Based on the nature of the mission to be costed, a combination of Parametric Cost Estimation techniques and Analogy-based estimation was used. Parametric Cost Estimation is ideal during early mission planning, while the Analogy based approach was deemed viable since other similar related missions (SOHO, Proba3, Darwin) could be identified and utilized for the SolmeX mission cost estimation. All values and parameters were the outcome of the SolmeX CEF Study held at the DLR Institute of Space Systems in Bremen from 1-4th November, 2010.

13.2. Cost Estimation Methodology Theory

The following chapter provides a brief description of the three main cost estimation methodologies discussed previously.

- ***Parametric Cost Estimation*** is based on a top-down approach, and employs a series of mathematical relationships which seek to relate cost to physical, technical and performance parameters that are known to strongly influence costs. Cost Estimating Relationships (CERs) express cost as a function of parameters. Complexity factors can also be applied to address deviations from underlying CER parameters and a particular mission. It is widely believed that early costing cannot be done effectively any other way.
- ***Engineering Build-Up (Bottom Up)*** cost estimation is a very specific approach, and is generally applied to a mission when all parameters at system and sub-system levels are clearly defined. By its nature, this approach requires a lot of time, resources and great detail, which is deemed inappropriate in this instance.

- **Analogy Cost Estimation**, as the name suggests, relies on a comparison between different precedent or existing programs which are deemed to be similar to the mission being costed. This approach requires intensive analyst judgement and adjustments for any differences between projects (i.e. project size, complexity, experience, technologies etc.), as well as sufficiently detailed data of the “compared” system as well as of the “new” system.

In order to obtain a relevant, indicative and valid cost estimate for a mission, it is essential to identify the most appropriate cost estimation approach on a case to case basis. It is then essential to select a tool/model which can be applied to obtain a cost estimate. In Figure 13-1 below is shown the adaptability of the three different methods in dependence on the single program phases.

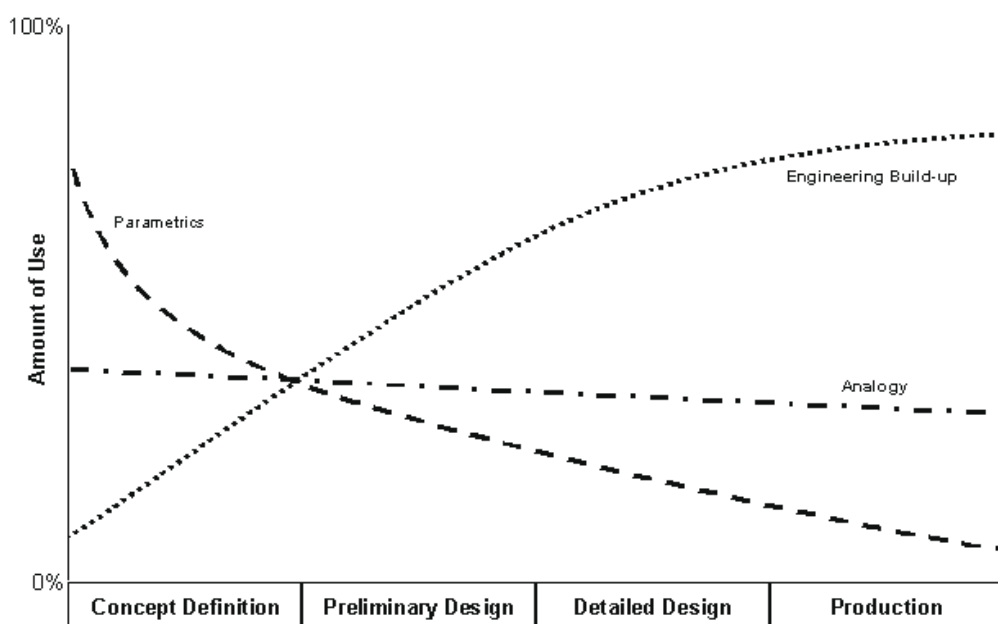


Figure 13-1: Cost estimation according to program phase.

Based on the preliminary nature of the mission to be costed, a combination of Parametric Cost Estimation techniques and Analogy-based estimation were used. Parametric Cost Estimation is ideal during early mission planning, while the Analogy based approach was deemed viable since other similar related missions (SOHO, Proba3, Darwin) could be identified and utilized for the SolmeX mission cost estimation with respect to the Operations cost evaluation.

It is also important to note that all costs are calculated within the framework of the 2010 fiscal year. Therefore relevant adjustments will have to be made to all figures (i.e. to factor in inflation etc) if this cost estimate is to be referred to at a future time.

13.2.1. Small Satellite Cost Model (SSCM2007)

The estimation of the SolmeX mission is realized predominantly with the aid of the Small Satellite Cost Model, Version 2007 (SSCM07), which was developed by the *Aerospace Corporation* [RD 6]. This model estimates subsystem and system-level cost for satellites, weighing less than 1000 kg using CERs derived from actual cost and technical parameters from 53 different small satellite missions. The SSCM uses cost elements from the following subsystems and elements:

- Attitude Determination and Control Subsystem (ADCS)
- Propulsion
- Power
- Telemetry, Tracking, and Command (TT&C)/Command and Data Handling (C&DH)
- Structure
- Thermal
- Assembly, Test, and Launch Operations (ATLO)
- Program Management (PM)/Systems Engineering (SE)

Figure 13-2 below shows a CER of the subsystem “Power” as used in the SSCM including the specific CER function, statistics (standard error, data range) and database of used former satellite missions. In this example the cost drivers for the CER are the mass of subsystem power (X1) and the battery mass (X2).

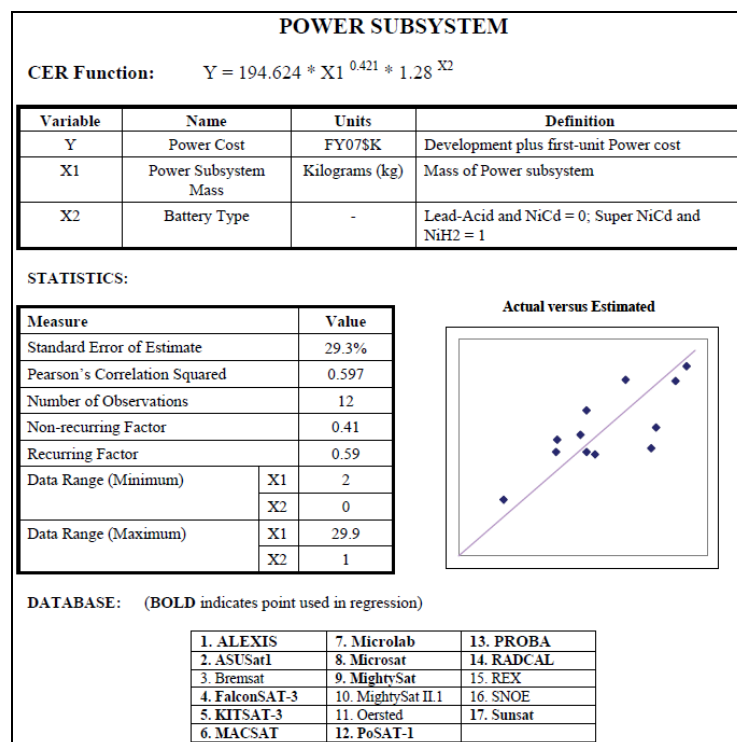


Figure 13-2: Cost Cost Estimation Relationship (CER) – Power Subsystem.

13.2.2. Cost Estimate Relationships (CERs)

Parametric cost estimates are a statistical cost analysis estimation method, where formula estimates, cost-to-cost estimates, or Cost Estimating Relationships (CER) estimates are based on mathematical expressions. The mathematical expressions are derived by statistically correlating historical cost data from several systems to physical performance characteristics of those same systems. The observed relationships between cost and the selected technical variables are treated as time-constant expressions of reality. The implicit assumption of this approach is that the same forces that affected cost in the past will affect cost in the future. The parametric estimate is ideally applied during pre-Phase A and Phase A studies when the subsystems are not yet clearly defined and exact information about the project is unavailable.

The key approach for the parametric estimating technique is a database consisting of former satellite mission data. This database provides technical data and the corresponding cost data. After normalization of the raw data to the same economical year or Fiscal Year (FY) a Cost Estimating Relationship (CER) can be built. The CER uses a characteristic of an item to predict its cost. Examples are CERs that estimate an item's manufacturing cost based on its mass (independent variable).

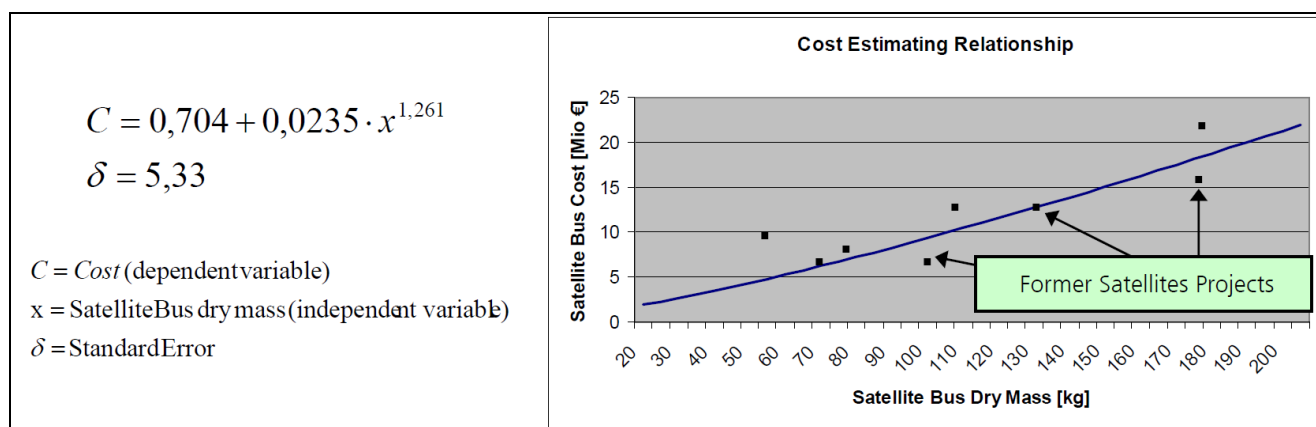


Figure 13-3: Example of a mathematical formula of a Cost Estimating Relationship (CER).

Therefore, the various data points are drawn on a scatter plot, where for example the X-axis depicts the satellite bus dry mass (independent variable) and the Y-axis depicts the total satellite bus cost (dependent variable). By using different OLS-Regression analysis methods as well as curve fitting methods a specific graph can be calculated, representing the relationship between the satellite bus dry mass and the total satellite bus cost. Figure 13-3 shows such a typical CER. The derived graph and so the CER can either be linear or nonlinear.

Additional to the regression analysis, the standard error (δ) can be calculated, which gives the user an impression of the sharpness or the quality of the used CER. Specifically, the standard

error estimates the standard deviation of the difference between the estimated values and the true (past) values.

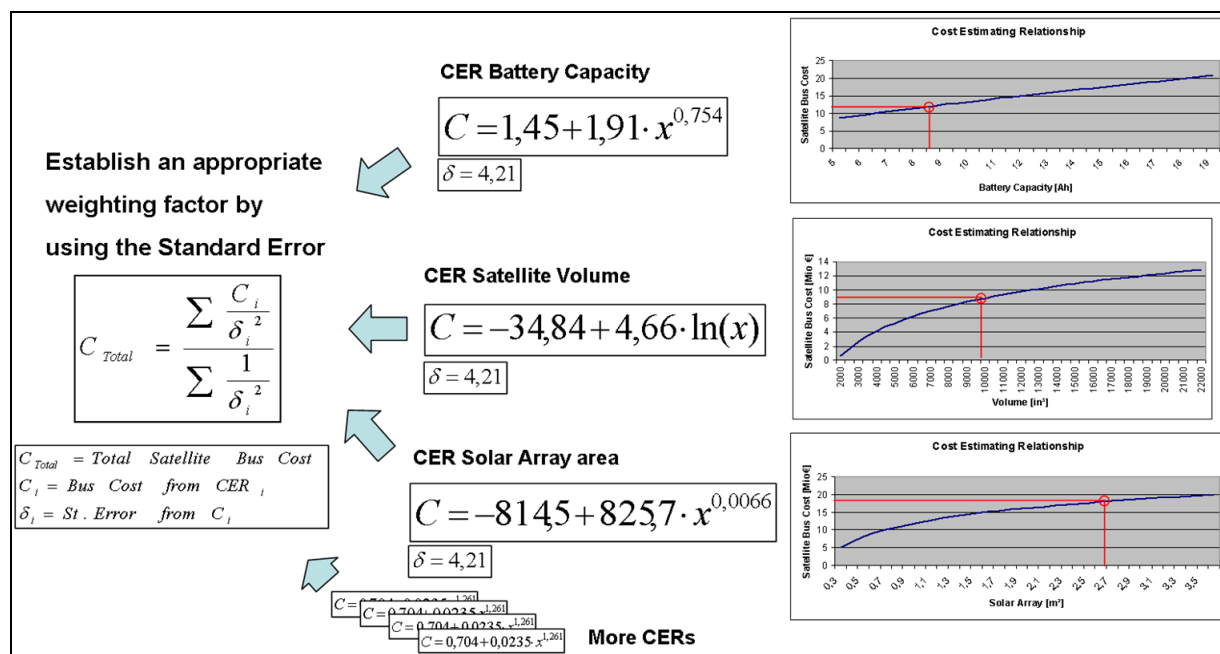


Figure 13-4: Parametric estimating procedure for calculating satellite cost by using several CERs. Left hand side: Weighted-average algorithm for final cost estimate.

The CER can be used to obtain independent estimates of the spacecraft bus cost. But it is more important to use several CERs simultaneously to reduce the effects of statistical outliers and special circumstances that typical occur in any program. To estimate the cost (C), a weighted average algorithm is employed, which is using the standard error (δ), of each CER to establish an appropriate weighting factor. Figure 13-4 shows the mathematical algorithm procedure to calculate the final end result.

13.3. SSCM Application to SolmeX

Although by definition the Coronagraph S/C falls outside the ‘small satellite’ category with its mass of 1364 kg, the SSCM is still deemed adequate to formulate a relevant cost estimate at this early mission planning phase. To compensate for the Coronagraph S/C mass being beyond the SSCM limits, a considerable contingency factor of 50% is therefore applied to the resulting SSCM cost estimate. This is based on the Coronagraph S/C standard error value (SSCM) of roughly 24 Million € (ROM 18%). This error is then roughly doubled to factor in the larger mass of the Coronagraph S/C craft than accounted for by the SSCM.

A smaller contingency factor of 20% is also applied to the SSCM output cost estimate for the Occulter S/C. Although this falls within definition of a ‘small satellite’, the SSCM output

indicates a 13 Million € (ROM 18%) standard error, so the standard overall contingency factor of 20% is deemed sufficient added on top of the SSCM estimate.

Consequently, the total cost of both SolmeX satellites (including launcher costs and operations costs) are then assigned a further 30% contingency factor, fortifying the probability of the result being well within the allocated ESA budget of €470 million.

13.4. Requirements

The maximum allocated ESA budget for the SolmeX mission is specified as being 470 Million €. Furthermore, a breakdown structure for this funding is suggested within [RD 2], as outlined below in Table 13-1.

Table 13-1: ESA Cost at Completion reference building blocks.

Activity	% of Total ESA CaC
Total spacecraft industrial activities	approx. 55%
Launcher services (assumes a SF-2B launcher from Kourou)	approx. 15 %
Ground segment and operations (MOC and SOC)	approx. 20 %
ESA project	approx. 10 %

13.5. Assumptions

To perform the CER-based cost estimation for the SolmeX mission, a series of assumptions have been made. These assumptions are divided into two categories, with one set relating to the SSCM while the second set addresses other assumptions necessary for the Analogy-based segment of cost estimation.

SSCM Assumptions

- Fiscal Year is 2010 [FY2010]
- The inflation methodology is taken from NASA, (an option which is integrated into the SSCM software)
- Ground equipment costs, as well as Phase E costs are not included
- Launch costs are not included in the SSCM output (estimated separately)
- Payload costs are not included

- The model estimates non-recurring costs (including design, drafting, engineering costs, a portion of PM and SE) as well as recurring cost (or theoretical first unit cost – including fabricating, manufacturing, LOOS, IA&T) based on the established CERs.
- A maximum specified mission lifetime was input into the SSCM to obtain costs for ‘worst case’ scenario
- The SSCM permits only one input per technical parameter.
 - *Structure* input options are one of *aluminium/composite*. In case of the Coronagraph S/C, the structure was designed from a combination of carbon fiber, aluminium and sandwich structures. Since the bulk of the structure was made from aluminium, *aluminium* was chosen. Similarly, aluminium was chosen as the prime structure material for the Occulter S/C.
 - *Propulsion* input options are one of *cold gas/hydrazine*. In case of the Coronagraph S/C, the propellant was taken to be hydrazine. For the Occulter S/C, while hydrazine is also utilised, the primary propellant was taken to be cold gas, which is required for the Occulter’s re-orbiting manoeuvres.

General Assumptions

- The most prolific assumption made within this cost estimate, is to apply the SSCM to a satellite which technically falls outside the definition of a ‘small satellite’. This inconsistency, however, was addressed with stringent contingency margins being applied to the resulting cost estimate, as discussed previously in Chapter 13.3.
- To formulate an Operations cost estimate using the Analogy-based approach, the SOHO [RD 10] as well as the Proba3 [RD 11] missions were deemed to both provide adequate and related references to estimate SolmeX Operations costs. Being an unprecedented mission of its kind, the scientific instruments on SOHO were complicated, and the mission was a very international mission, in its nature incurring significant operations costs. In comparison, the proposed SolmeX mission will be predominantly ESA operated (one NASA science instrument is foreseen), the technology of the instruments onboard is less novel, and therefore the Operations costs are not expected to exceed those of the SOHO mission [RD 10].
- It is important to note that all costs are calculated within the framework of the 2010 fiscal year. For the case of currency conversion, any dollar values throughout this report (i.e. SSCM output is in USD) have been converted to a Euro currency to allow

for a common comparison. This has been done using the exchange rate at the time of the CEF study (1€ = 1.3983 USD). Therefore relevant adjustments will have to be made to all figures (i.e. to factor in inflation etc) if this cost estimate is to be referred to at a future time.

13.6. Cost Distribution

Table 13-2 below shows the overall cost estimate distribution across the three areas of satellite development and manufacture, launch costs and mission operation costs over the planned three year life of SolmeX. Satellite Costs were derived using the SSCM results. Launch Costs were obtained factually, while Operations Costs were derived using an Analogy-based approach.

Table 13-2: SolmeX mission cost estimate breakdown.

COST	million €	%
Satellites Cost	270.43	59.2%
Launch Costs	58.5	12.8%
Operations Cost	127.85	28.0%
TOTAL SOLMEX COST	456.78	100.0%

A further visual breakdown of the SolmeX satellite cost estimate distribution (system and subsystem level), obtained from the SSCM is provided below. Table 13-3 presents a cost breakdown for the Coronagraph S/C, while Table 13-4 shows the cost breakdown for the Occulter S/C. Seven subsystems of Thermal, Power, Structure, ADCS, Propulsion, Communications and Data Handling (C&DH) and Telemetry Tracking and Control (TT&C) are represented. From a system perspective, the four areas of Launch and Orbit Operations Support (LOOS), Program Management and Systems Engineering (PM/SE), Integration, Assembly and Test (IA&T), and the System Bus are represented.

Here, it is also interesting to compare the resulting SolmeX cost estimation distribution to the values specified for a typical ESA mission. The average range of fractional cost for the main building blocks which enter into the Cost at Completion models, assuming an overall mission cost of 470 ME (e.c. 2010), are shown below in Table 13-5.

Table 13-3: Coronagraph S/C System and Subsystem Cost Breakdown.

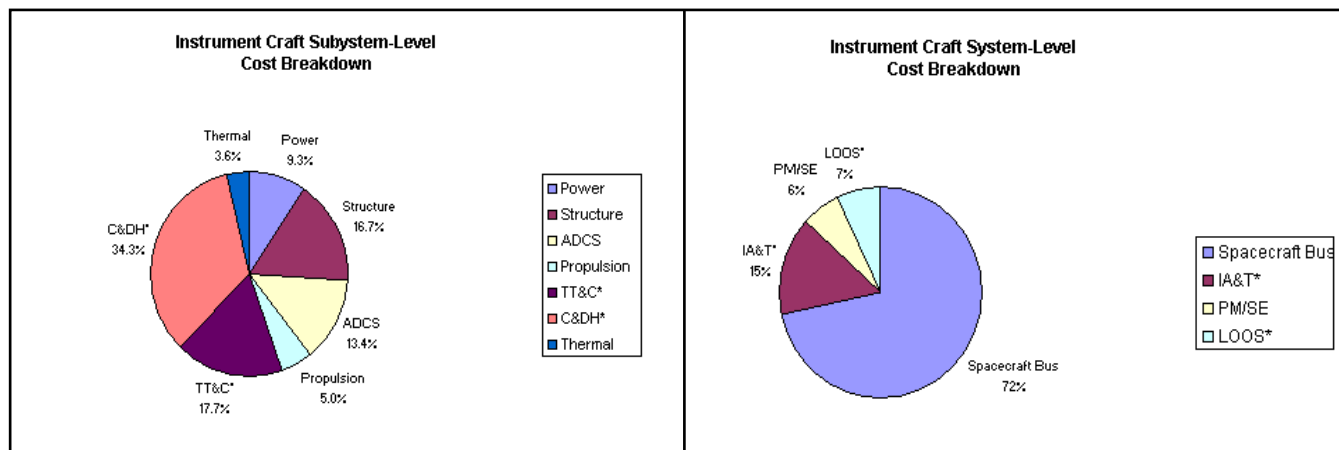


Table 13-4: Occulter S/C System and Subsystem Cost Breakdown.

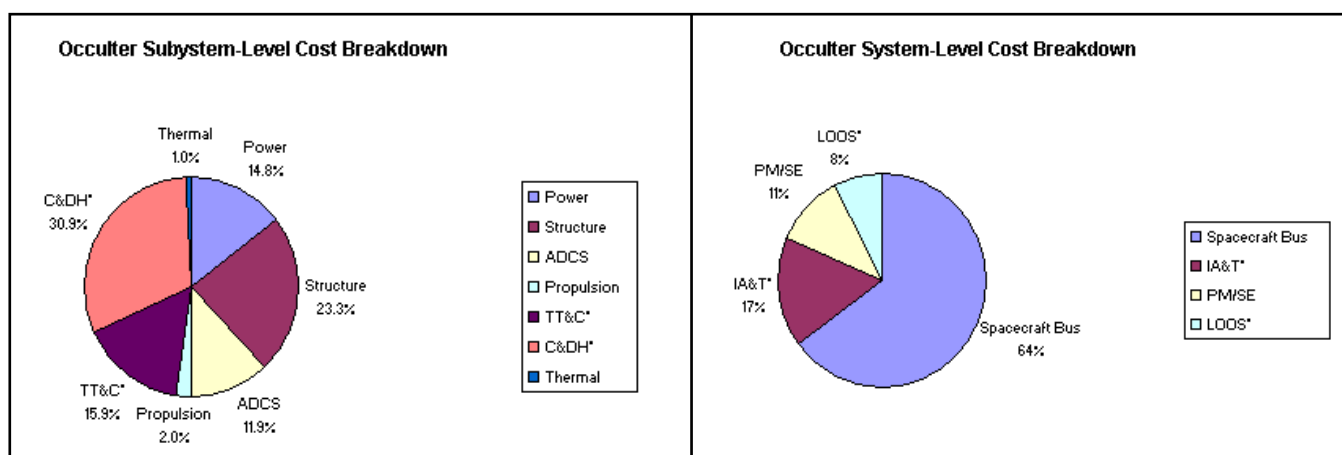


Table 13-5: ESA Cost at Completion reference building blocks.

Activity	% of Total ESA CaC
Total spacecraft industrial activities	approx. 55%
Launcher services (assumes a SF-2B launcher from Kourou)	approx. 15 %
Ground segment and operations (MOC and SOC)	approx. 20 %
ESA project	approx. 10 %

A direct comparison can be made here with the same allocation of values obtained for the SolmeX mission cost estimation. This is shown below in Table 13-6.

Table 13-6: SolmeX compared to ESA Cost at Completion reference building blocks.

Activity	% of Total ESA CaC	% of Proposal Cost Estimate		% SolmeX Cost Estimate
Total spacecraft	approx. 55%	Coronagraph S/C (plus 50% IA&T)	32.2%	45.8%
Industrial activities		Occulter (plus 50% IA&T)	13.5%	
Launcher services (SF-2B launcher from Korou)	approx. 15%	Soyuz Launch Vehicle	12.8%	17.1%
		LOOS	4.3%	
Ground segment and operations (MOC and SOC)	approx. 20%	Operations	28.0%	28.0%
ESA project costs	approx. 10%	PM/SE Segment	4.5%	9.1%
		IA&T Segment (50%)	4.6%	

It can clearly be seen that the resulting SolmeX cost distribution is very well correlated to that of the proposed ESA cost breakdown.

For the SolmeX mission cost distribution, *Total spacecraft industrial activities* were taken to be the System Bus cost estimate from SSCM, plus 50% of the IA&T Segment costs, since a portion of the integration, assembly and testing should be borne in the development stages. Table WT shows these costs split up accordingly between the Coronagraph and Occulter S/Cs. In addition, the LOOS segment from the SSCM cost estimate was also assigned to the Launch costs segmentation, while PM/SE and the remaining 50% of the IA&T costs were attributed to the ESA project costs, since ESA involvement is deemed necessary during a part of the integration, assembly and testing.

13.6.1. Development and Satellite Industrial Activity Costs

This segment of the SolmeX cost estimation was carried out using Small Satellite Cost Model (SSCM). For the Parametric cost estimation of the SolmeX mission, the SSCM needs values from a limited number of technical parameters for each of the elements of SolmeX. Table 13-7 and Table 13-8 below list the input technical parameters required by the SSCM. All values were derived from the relevant subsystem IDMs of the CEF Session held at the Bremen DLR Institute of Space Systems (1-4th November, 2010). Table 13-7 shows the technical parameters input into the SSCM for the SolmeX Coronagraph S/C, while Table 13-8 shows the inputs for the Occulter S/C cost estimation calculation.

Table 13-7: Technical Input Parameters for the Solmex Coronagraph S/C.

Technical Parameter (Coronagraph S/C)	Value
Programmatic	
Development Time [months]	24
Fiscal Year for Estimate [yyyy]	2010
Inflation Methodology	NASA
System	
Destination	Planetary
Maximum Distance from Sun (AU)	1
Design Life [months]	72
Satellite Wet Mass [kg]	1363
Power	
Solar Array Mounting Type	Deployed-Fixed
BOL Power [W]	1182.5
Structure	
Primary Structure Material	Aluminum
Structure Subsystem Mass [kg]	370
ADCS	
Stabilization Type	3-axis
Star Tracker?	Yes
ADCS Subsystem Mass [kg]	81.4
Pointing Control [deg]	5.556E-05
Propulsion	
Propellant Type	Hydrazine
Monopropellant or Bipropellant?	Monopropellant
Propulsion Subsystem Dry Mass [kg]	295
TT&C/C&DH	
TT&C/C&DH Subsystem Mass [kg]	21
Transmit Power [W]	70
Thermal	
Thermal Subsystem Mass [kg]	33

Table 13-9 and Table 13-10 below offer a further overview of the observance of technical input parameters and associated values for the SolmeX mission within the required data range for the SSCM inputs. Parameters for the Coronagraph and Occulter S/Cs are shown separately.

The red figures seen in Table 13-9 are indicative of input values entered into the SSCM which lie beyond the range of expected values for ‘small satellites’ (defined as being under 1000 kg). In the case of the Coronagraph S/C, the figures which extend beyond the SSCM range apply to the satellite wet mass (hence also Structure subsystem), as well as the ADCS (Pointing Control), Propulsion and Power subsystems. All of these ‘anomalies’ can be attributed to the fact that the Coronagraph S/C exceeds the 1000 kg ‘small satellite’ benchmark.

Table 13-8: Technical Input Parameters for the Solmex Occulter S/C.

Technical Parameter (Coronagraph S/C)	Value
Programmatic	
Development Time [months]	24
Fiscal Year for Estimate [yyyy]	2010
Inflation Methodology	NASA
System	
Destination	Planetary
Maximum Distance from Sun (AU)	1
Design Life [months]	72
Satellite Wet Mass [kg]	715
Power	
Solar Array Mounting Type	Deployed-Fixed
BOL Power [W]	537.5
Structure	
Primary Structure Material	Aluminum
Structure Subsystem Mass [kg]	207
ADCS	
Stabilization Type	3-axis
Star Tracker?	Yes
ADCS Subsystem Mass [kg]	54
Pointing Control [deg]	0.016667
Propulsion	
Propellant Type	Cold Gas
Monopropellant or Bipropellant?	Monopropellant
Propulsion Subsystem Dry Mass [kg]	4
TT&C/C&DH	
TT&C/C&DH Subsystem Mass [kg]	10
Transmit Power [W]	10
Thermal	
Thermal Subsystem Mass [kg]	6

To factor in for this in the final cost estimate, a significant contingency margin has been applied to the final SSCM estimate for the Coronagraph S/C (see Chapter 13.3).

The Occulter S/C fits the classification of a ‘small satellite’ with its wet mass of 715 kg. The only red figures seen in Table 13-10 relate to the Propulsion and Thermal subsystems. Both of these ‘anomalies’ in values should be of no concern here due to the nature of the Occulter S/C, which only acts as a functional shield for the Coronagraph S/C.

Nevertheless, a contingency factor is still applied to the final SSCM cost estimate for the Occulter (see Chapter 13.3).

Table 13-9: Overview of SolmeX Coronagraph S/C input data with respect to SSCM range of values.

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time		22	24	48	
Maximum Distance from Sun		1	1	2.7	
Design Life		6	72	96	
Satellite Wet Mass		165	1363	787.8	73.0%
BOL Power		150	1182.5	1880	
Structure Subsystem Mass		19.96	370	236	56.8%
ADCS Subsystem Mass		2,8	81.4	58.5	39.1%
Pointing Control	99.7%	0,017	5.6E-05	3	
Propulsion Subsystem Dry Mass		8,7	295	118,2	149.6%
TT&C/ C&DH Subsystem Mass		8,7	21	48.98	
sTransmit Power		1	70	15	366.7%
Thermal Subsystem Mass		6.57	33	56	

Table 13-10: Overview of SolmeX Occulter S/C input data with respect to SSCM range of values.

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time		22	24	48	
Maximum Distance from Sun		1	1	2.7	
Design Life		6	72	96	
Satellite Wet Mass		165	715	787.8	
BOL Power		150	537.5	1880	
Structure Subsystem Mass		19.96	207	236	
ADCS Subsystem Mass		2,8	54	58.5	
Pointing Control		0,017	0.017	3	
Propulsion Subsystem Dry Mass	54.0%	8,7	4	118,2	
TT&C/ C&DH Subsystem Mass		8,7	10	48.98	
Transmit Power		1	10	15	
Thermal Subsystem Mass	8.7%	6.57	6	56	

Table 13-11 and Table 13-12 below provide an overview of the technical parameters and the associated cost estimate values obtained from the SSCM. Here TT&C and C&DH are

combined within the SSCM program. Those two subsystems are estimated using a single CER and are then split into separate subsystem estimates. The standard error is kept as a single value.

Table 13-11: Cost estimation for SolmeX Coronagraph S/C [k€, FY2010].

	Estimate (FY10\$K)				% of Sub-level	% of Sys-level
	Non-rec	Rec	Total	Std Error		
Spacecraft Bus Subsystems						
Power	3,631	5,224	8,855	3,595	9.3%	
Structure	8,709	7,126	15,835	5,938	16.7%	
ADCS	6,359	6,359	12,717	3,357	13.4%	
Propulsion	1,596	3,098	4,694	1,671	5.0%	
TT&C*	8,721	8,050	16,771	18,547	17.7%	
C&DH*	16,929	15,627	32,555	0	34.3%	
Thermal	1,818	1,549	3,366	1,535	3.6%	
Spacecraft Bus	47,762	47,032	94,794	20,213	100%	71.4%
IA&T*	10,923	9,447	20,369	12,546		15.3%
PM/SE	4,032	4,368	8,400	2,579		6.3%
LOOS*	0	9,151	9,151			6.9%
S/C Development & First Unit	62,717	69,998	132,715	23,930		100%

Table 13-12: Cost estimation for SolmeX Occulter S/C [k€, FY2010].

	Estimate (FY10\$K)				% of Sub-level	% of Sys-level
	Non-rec	Rec	Total	Std Error		
Spacecraft Bus Subsystems						
Power	3,017	4,341	7,357	2,987	14.8%	
Structure	6,361	5,204	11,565	4,337	23.3%	
ADCS	2,950	2,950	5,900	1,558	11.9%	
Propulsion	346	671	1,016	362	2.1%	
TT&C*	4,111	3,795	7,906	8,743	15.9%	
C&DH*	7,981	7,367	15,347	0	31.0%	
Thermal	260	221	481	219	1.0%	
Spacecraft Bus	25,025	24,549	49,574	10,334	100%	64.8%
IA&T*	6,851	5,925	12,776	7,869		16.7%
PM/SE	4,032	4,368	8,400	2,579		11.0%
LOOS*	0	5,740	5,740			7.5%
S/C Development & First Unit	35,908	40,583	76,491	13,242		100%

It can be seen that the expected cost of the SolmeX Coronagraph S/C is 132.7 Million € [FY2010] without Operations and Launch. The Non-recurring costs are 62.7 Million € while the Recurring cost is approximately 70 Million €.

The standard error for this estimate is approximately 24 Million €. In a best case scenario the total cost would be reduced to 108.8 Million €, while a worst case scenario would raise the cost to 156.6 Million €. In this case, the median value is taken, since significant contingency margins are already applied to the final SSCM cost estimate for the Coronagraph S/C.

Similarly for the Occulter craft, the expected bus cost obtained from the SSCM is 76.5 Million € [FY2010] without Operations and Launch costs. The Non-recurring costs are then 35.9 Million € while the Recurring cost is 40.6 Million €.

The standard error for this estimate is approximately 13 Million €. In a best case scenario the total cost would be reduced to 63.2 Million €, while a worst case scenario would raise the cost to 89.7 Million €. Again, the median value is taken here, since adequate contingency margins are already applied to the final SSCM cost estimate for the Occulter.

13.6.2. Launch Services

Launcher Services, according to the ESA requirements [RD 2] is specified to be a Soyuz Fregat launch vehicle, launched from French Guiana.

Using the Analogy-based cost estimation method, the cost of a Soyuz Fregat Launch vehicle was determined to be approximately €45 million if launched from Kourou in the 2010 fiscal year. This value was extracted from the Federal Aviation Administration's *Semi-Annual Launch Report: Second Half 2009* [RD-9]. A cost adjustment would be necessary to factor in effect of inflation etc., if the launch was to be costed within a later timeframe. Logically, it can be foreseen that launch prices will vary between the time of this cost estimate and potential launch date for the SolmeX mission in 2022.

13.6.3. Operation

For this part of the cost estimation, the Analogous cost estimation technique was applied. Based on data from the SOHO mission, as well as the Proba3 project [RD-10 and RD-11], the estimate for operations of SolmeX were given as being €30 million per annum, for the minimum duration of 3 years. Furthermore, an inflation index of 3% per year was also applied.

13.7. Summary

To estimate the cost of the SolmeX mission, parametric cost estimation was used as the main cost estimation technique. Parametric cost estimation is easy to apply, is highly variable and adaptable to rapid and dynamic changes in design, as encountered in the CEF environment. Parametric cost estimation is also highly compatible to the IDM Excel sheets which form the backbone of the interdisciplinary data exchange throughout a CEF Study.

Table 13-13: Cost Distributions for SolmeX Coronagraph S/C.

INSTRUMENTATION SATELLITE COST ESTIMATE (SSCM V7)	
	133 million \$
	95 million €
50% contingency margin	142.37 million €
LAUNCH VEHICLE COST ESTIMATE (Soyuz Fregat)	
Soyuz Fregat	45.00 million €
OPERATIONS COST ESTIMATE	
Annual Cost	30 p.a.
Mission Life	3 years
Inflation (p.a.)	3 %
Total Operations Cost (+ 3% infl)	98.35 million €
TOTAL MISSION COST ESTIMATE	
	285.71 million €
TOTAL MISSION COST ESTIMATE (contingency factor 30%)	
	371.43 million €

The Small Satellite Cost Model (SSCM), Version 2007, was used as a parametric tool to estimate the cost for the SolmeX Coronagraph and Occulter satellite buses. Furthermore, an analogy-based approach is used to derive a cost estimate for the SolmeX Operations costs. Factual information is used to formulate a cost estimate for the SolmeX mission launch costs..

A summary of the segmented SSCM cost estimates for the Coronagraph S/C as well as the Occulter S/C is provided in Table 13-13 and Table 13-14.

Table 13-14: Cost Distributions for SolmeX Occulter S/C.

OCCULTER SATELLITE COST ESTIMATE (SSCM V7)	
	77 million \$
	55 million €
20% contingency margin	65.66 million €
LAUNCH VEHICLE COST ESTIMATE (Soyuz Fregat)	
	0 million €
OPERATIONS COST ESTIMATE	
Annual Cost	0 p.a.
Mission Life	3 years
Inflation (p.a.)	3 %
Total Operations Cost (+ 3% infl)	0 million €
TOTAL MISSION COST ESTIMATE	
	65.66 million €
TOTAL MISSION COST ESTIMATE (contingency factor 30%)	
	85.35 million €

Since the Coronagraph and Occulter satellites belong to a common mission, they share common launch and operations costs (included for the Coronagraph S/C, and omitted for the Occulter S/C in Table 13-13 and Table 13-14 above).

A summary of the cost estimation for the SolmeX mission is shown in Table 13-15 below:

Table 13-15: Summary of the SolmeX mission costs.

COST	million €	% of Mission Total
Satellites Bus Cost	270.43	59.2%
Launch Costs	58.5	12.8%
Operations Cost	127.85	28.0%
TOTAL SOLMEX COST	456.78	100.0%

Therefore the outcome of the preliminary costing study indicates that the design, development, integration, testing, launch as well as ground operations for the SolmeX mission are achievable within the allocated ESA budget of 470 Million €. Within the cost estimate, consistent contingency margins were applied, which suggests that the project can potentially be realised well under budget. Payloads were not included in this cost estimation.

14. CEF-Support

Study work in a CE facility is particularly efficient, enriching and a potential driver, given its dense interactional nature and the highly simultaneous, multi-layered workflow. The SOLMEX study is of particular interest as it requires a relatively advanced level of technology development, bringing together a broad range of engineering and mission aspects as well as a complex scientific (costumer) demand, with Solmex being a solar exploration. Therefore, Solmex represents an ideal context for **conducting research into the very nature of the processes of development and innovation as fostered by the CE facility.**

Various issues are at stake when it comes to quality of such dense working processes, the (micro-) genesis of ideas and the suitable management of multivoiced conversations on conceptual development and object/space-craft design, involving - amongst others - highly complex tools (e.g., scaled drawings, preliminary calculations, metaphors, experience accounts etc.) for “talking the spacecraft and/or mission” into being. Concurrent engineering processes raise indeed questions, which call for further investigation and detailed analysis. Such research should be concerned with domains as (non exhaustive list):

- The emergence of critical instances (e.g., conceptual/linguistic/perspective-bound misunderstandings),
- Deviations in the perception of efficiency amongst participants within a running CE study / CE process,
- Suitable use of space and available tools within the facility,
- Quality indicators of the deployment of the process (e.g., relevant/beneficial stagnations in the deployment of the process vs. avoidable iterations),
- Interaction flow and its management in line with knowledge construction,
- The efficient use of instruments of knowledge management (e.g., data-bases),
- The critical level for leveraging (by means of goal-driven interventions for instance) innovation in line and/or beyond the scope of the study at hand.

DICA-lab within the Unit for sociocultural research on learning and development at the University of Luxembourg focuses on the analysis of **processes of development** in heterogeneous cultural (e.g., English as lingua franca in scientific contexts, multilingual expertise) as well as complex technological contexts (e.g., science learning, media-mediated communication, intervention potential in tool-mediated activities). Studies are concerned with the **empirical tracing and analysis** of the (micro-)genesis of ideas, the identification of moments of potential intervention, leveraging innovation and the assurance of (indicators of) quality in development and learning.

Five researchers managed the explanatory study during the CEF Solmex study:

- 2 senior researchers (specializing in tools mediating (science) development (Prof. Dr. Charles Max) and interaction analysis (Assoc.-Prof. Dr. Gudrun Ziegler)

- 2 advanced junior researchers (space systems engineer, specializing in concurrent engineering processes (Hubert A. Moser) and stance-taking in interaction (Adrienne Lambo Ouafo))
- 1 junior researcher (specializing in tool-/model-bound science learning (Martin Kracheel))

80 hours of raw audio-visual data were collected during the Solmex study using the inbuilt video-conferencing facility and three mobile cameras with directional microphones, plus up to five digital audiorecorders. All activities within the CEF during the time of the study were recorded, additionally five individual and two group conversations were conducted (10 hours in total), discussing elements, which emerged from the 4-day-long working session.

All data are/will be digitalized and systematically organized in an analytical database, which allows for indexing and subsequent detailed analysis. Collections of phenomena will be building and analyzed from the micro analytical transcripts of the data (1 hour of recording requires up to 80 hours of work for creating and treating the analytically relevant, technically suitable artifact of the transcript).

In line with the identified domains of analysis, a first report with example elements will be submitted to DLR by January 2011 in order to narrow down the analysis to a limited set of sub-domains which are most relevant for assuring quality in the CEF study processes and fostering the potential of CEF study participants and therefore, the study projects.

15. Acronyms

Domain	Abbreviation	Comments
General		
	BOL	Begin of Life
	CEF	Concurrent Engineering Facility
	CS	Coronagraph Spacecraft
	DLR	Deutsches Zentrum für Luft- und Raumfahrt
	EOL	End of Life
	ESA	European Space Agency
	G	Goal
	H/K	Housekeeping
	OS	Occulter Spacecraft
	P/L	Payload
	S/C	Spacecraft
	T	Threshold
	TBC	To Be Confirmed
	TBD	To Be Defined
	TRL	Technology Readiness Level
Mission Mission Analysis		
	FOP	Flight Operations Plan
	GEO	Geostationary Orbit
	HEO	High Elliptical Orbit
	HGA	High Gain Antenna
	L ₁	Libration Point 1
	NEP	North Ecliptic Pole
	RLP	Rotating Libration Point
	SEZ	Solar Exclusion Zone
System		
	FAM	Formation Acquisition Mode
	LM	Launch and Early Operation Mode
	MM	Manoeuvre Mode
	ScM	Science Mode
	SfM	Safe Mode
	TM	Transfer Mode
P/L Instruments		
	ChroME	Chromospheric Magnetism Explorer
	CUSP	Coronal Ultraviolet Spectropolarimeter

	EIP	Extreme Ultraviolet Imaging Polarimeter
	EIS	
	EIT	
	EUV	Extreme Ultraviolet
	GSFC	
	HAO	
	IAC	Instituto Astrofisica de Canarias
	INAF	
	NRL	
	RAL	Rutherford Appleton Laboratory
	SUSP	Scanning Ultraviolet Spectropolarimeter
	SWAP	
	UVCS	
	VIRCOR	Visible Light and Infrared Coronagraph
DHS Data Handling System		
	AOCS	Attitude and Orbital Control System
	BLOB	Binary Large Object
	HW	Hardware
	OBC	On-Board Computer
	OS	Occulter Spacecraft
	P/L	Payload
	S/C	Spacecraft
	SW	Software
Comms Communication		
	BER	Bit Error Rate
	CCD	Charge-coupled Device
	EIRP	Effective Isotropic Radiated Power
	G/S	Ground Station
	HPBW	Half power (-3dB) beam width
	ITU	International Telecommunication Union
	RF	Radio Frequency
	S/C	Space craft
	SSPA	Solid State Power Amplifier
	TRL	Technology Readiness Level
	TT&C	Telemetry, Tracking and Command
	TWTA	Travelling Wave Tube Amplifier
	UHF	Ultra High Frequency
Power		
	BCR/ BDR	Battery Charge Regulator/ Battery Discharge Regulator

	DoD	Depth of Discharge
	$P_{d,coronagraph}$	Power Demand of the Coronagraph S/C
	$P_{d,occulter}$	Power Demand of the Occulter S/C
	PCU	Power Conversion Unit
	PCDU	Power Conversion and Distribution Unit
	PDU	Power Distribution Unit
	S/G	Solar Generator
Thermal		
	MLI	Multi Layer Insulation
	q_{ext}	external heat load = $q_{ir} + q_{sol}$
	TCS	Thermal Control System
	TRP	Temperature Reference Point
AOCS Attitude Determination and Control		
	CLS	Coarse Lateral Sensor
	DoF	Degree of Freedom
	DWI	Dual Wavelength Laser Interferometer
	FFRF	Formation Flying Radio Frequency
	FoV	Field of View
	LoS	Line of Sight
	SRP	Solar Radiation Pressure
Configuration		
	AOC	Attitude and Orbital Control
Structure and Mechanisms		
	CoG	Centre of Gravity
Propulsion		
	AOC	Attitude and Orbit Control
	Isp	Specific Impulse
	N_2	Nitrogen
	N_2H_4	Hydrazine
	PMT	Proportional Micro Thruster
CEF Support		
Cost		
	ADCS	Attitude Determination and Control Subsystem
	C&DH	Command & Data Handling
	CE	Concurrent Engineering
	CER	Cost Estimating Relationship
	DLR	German Aerospace Center
	FY	Fiscal Year

	IA&T	Integration, Assembly & Test
	IDM	Integrated Design Model
	LOOS	Launch and Orbital Operations Support
	Non-Rec	Non-Recurring Cost
	PM	Program Management
	Rec	Recurring Cost
	S/S	Subsystem
	SE	System Engineering
	SSCM	Small Satellite Cost Model
	TT&C	Telemetry, Tracking & Command

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